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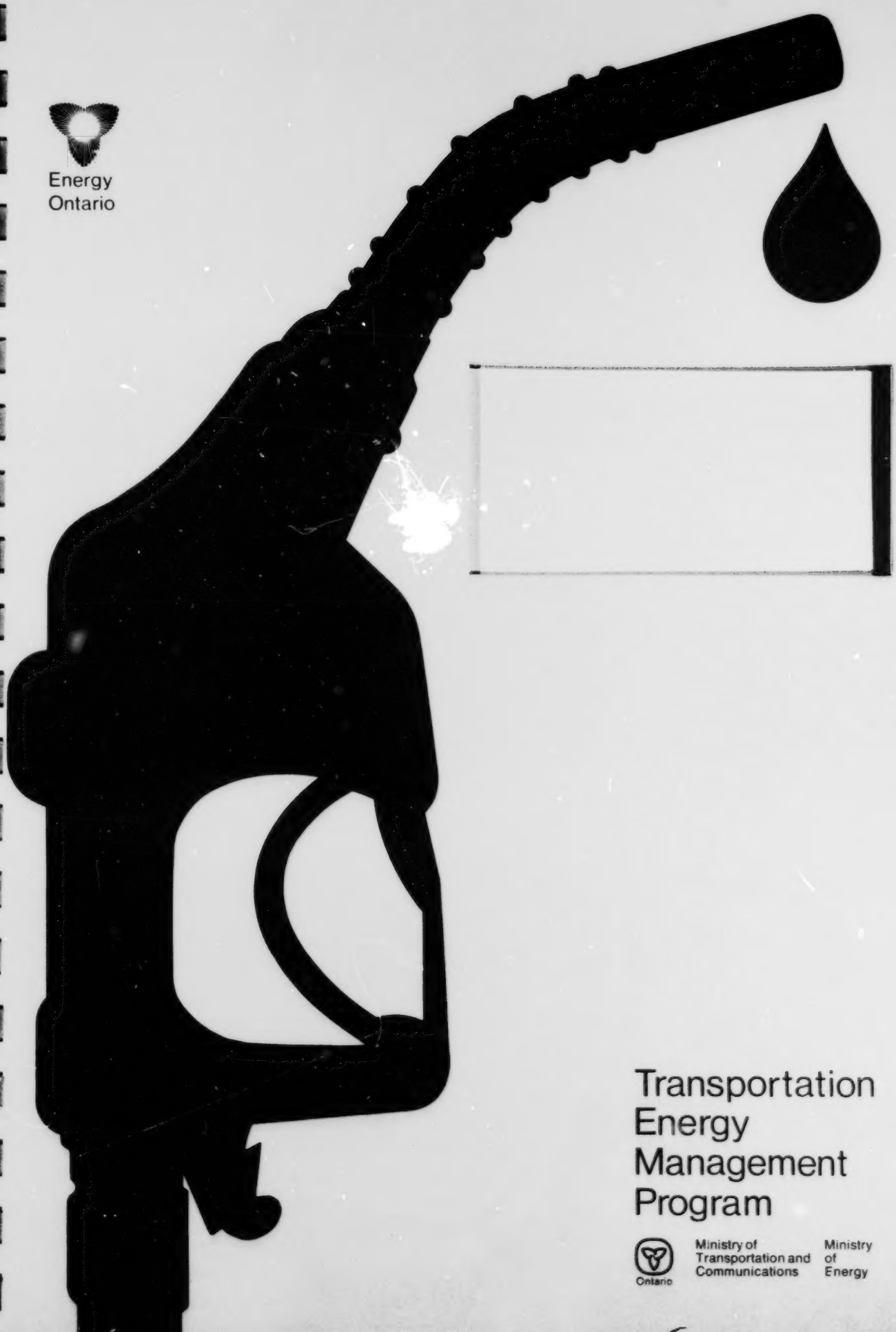

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NG-84-03

Testing and Evaluation of Automotive Natural Gas Conversion Equipment-Phase 1

NG-84-03

Testing and Evaluation of Automotive Natural Gas Conversion Equipment -Phase 1-

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Abstract:
A test program has been carried out on a FORD 4.9 L (300 CID) to evaluate the results of conversion to natural gas (NG) fuel and to compare four available NG carburation systems -- AFS ("Diversified Fuel Components"), IMPCO, BEAM and CNG.
During the program the power at WOT, specific fuel consumption and emissions at different speeds and loads have been monitored and compared with the baseline test on gasoline. The power developed using NG is 12 to 22% lower than for gasoline and the energy efficiency is reduced by 14 to 26% as an average for all systems tested. Hydrocarbons emission is increased. Through timing and air-fuel ratio optimization, an improvement of economy at partial loads of 2 to 8% was achieved. More basic research is required to increase the efficiency of natural gas use as automotive fuel.

Key Words: Gasoline, AFS, IMPCO, BEAM, CNG, air-fuel ratio,

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ABSTRACT

A test program has been carried out on a FORD 4.9 L (300 CID) engine to evaluate the results of conversion to natural gas fuel for vehicles (NGV) and to compare four available NG carburation systems -- AFS ("Diversified Fuel Components"), IMPCO, BEAM and CNG.

During the program the power at wide-open throttle (WOT), specific fuel consumption and emissions at different speeds and loads have been monitored and compared with the baseline test on gasoline. The power developed using NGV is 12 to 22% lower than for gasoline and the energy efficiency is reduced by 14 to 26% as an average for all systems tested. Hydrocarbons emission is increased. Through timing and air-fuel ratio optimization, an improvement of economy at partial loads of 2 to 8% was achieved.

More basic research is required to increase the efficiency of natural gas use as automotive fuel.

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EXECUTIVE SUMMARY

The large resources of natural gas available in Canada make its use very attractive as an automotive alternative fuel. The big advantage of replacing a percentage of the petroleum fuels at a low cost is somewhat counterbalanced, for the moment, by the incipient level of development of the technology for this application. Difficulties in the on-board storage of a reasonable quantity of fuel and in the creation of a network of fuel supply stations are a first area of concern. The development of the engines and fuel metering systems to use this fuel at a high level of energy efficiency is a second area requiring research work.

This study was initiated by the Ministry of Transportation and Communications (MTC) to assess the performance, economy and emissions of a representative spark-ignition engine converted to natural gas through accepted techniques and using commercially available carburation systems. The tests have been performed on an engine dynamometer, at fixed points of load and speed. This technique is very reliable in comparing the values between the baseline test on gasoline and the converted natural gas setting, in controlled laboratory conditions. The accuracy of the results is in the order of ±2% of readings. At the same time, caution has to be exerted in translating the results to real driving, where numerous transient regimes of load and speed are encountered.

The results of the test program can be summarized as follows:

1/ Significant Decrease in Engine Performance at wide-open throttle (Maximum Power):
With the four conversion kits tested (i.e., AFS, IMPCO, BEAM and CNG kits) maximum power suffers by 12.6-22.1%. The exact magnitude of the performance loss depends on the engine speed and conversion kit selected.

2/ A Significant Increase in Brake Specific Energy Consumption:
In general, conversion to natural gas is accompanied by significant increase in the brake specific energy consumption, i.e., a loss of efficiency. This loss depends on the engine load and speed as well as the conversion kit considered. The range of brake specific energy

consumption change is wide, and it includes as its extremes an improvement of 11.3% and a deterioration of 51.2%. The improvement is not typical and it is realized with only one of the kits at idle. For instance, with the CNG conversion kit and at 33% load, brake specific consumption is always higher than with gasoline by 30-50% -- a surprisingly large decline in efficiency. Among the four kits tested, the AFS kit appears to be the most promising with respect to energy efficiency. However, even with the "best" kit, engine efficiency with natural gas is inferior to that with gasoline except at a few specific engine operating points.

3/ Optimization of Spark-Timing and Air-Fuel Ratio has the Potential of Enhancing Part-Load Efficiency by 2-8%:
At 33% and 66% load brake specific fuel consumption with the AFS kit can be improved by 2-8% depending on the engine load and speed considered. This is accomplished by adjusting the spark-timing and the air-fuel ratio. The effect of spark-timing on fuel consumption is found to be significant. The optimum spark delay that minimizes the BSFC is determined by measuring fuel consumption at 3 or 4 timing points for each engine load and speed considered. The effect of the air-fuel ratio on fuel consumption is found to be less significant.

4/ Engine performance at WOT (Maximum Power) cannot be increased over and above the level achieved by commercial kits by air-fuel ratio and spark-timing optimization.

5/ Increased ignition energy, spark gaps and voltage show little or no effect on performance and fuel economy. Increasing the gap of the spark-plugs and the spark voltage, simultaneously, appears to promise a modest (2-3%) reduction of park-load specific fuel consumption.

6/ Resetting of the cooling water thermostat to 71°C results in a 9-14% increase in specific fuel consumption.

7/ Disconnection of the Exhaust Gas Recirculation (EGR) valve results in 10-15% increase in specific fuel consumption.

8/ The level of exhaust emission of hydrocarbons (expressed as methane and measured before the catalytic converter) is much higher with natural gas than with gasoline. This observation suggests the occurrence of incomplete combustion. CO and NO_x emission levels are comparable to those experienced with gasoline.

9/ The average temperatures in the exhaust system before the catalytic converter are consistently lower than those measured with gasoline.

10/ The Air-Fuel Ratio Schedule of the Gasoline Carburettor is not Closely Followed by Any of the CNG Conversion Systems:
Specifically, the gasoline carburettor produces a stoichimetric or slightly rich mixture at the extremes of the load range, i.e., no load and full load conditions, and a rather lean mixture at partial load. This schedule results in a compromise between good performance/driveability and fuel economy. The CNG conversion kits seem to be unable to follow this schedule. Instead, they produce a progressively richer mixture with increasing load with a too lean idle mixture and not sufficiently lean part-load mixture.

This condition, may explain the general observations of rough idle and poor part-load fuel economy.

11/ The study indicates that the observed deficiencies in power and fuel economy may be due to the inability of the CNG mixers to supply the correct air-fuel mixture and to lower flame speed resulting in incomplete combustion.

This last aspect needs basic combustion research to clarify the means of improving the energy efficiency of natural gas use as an automotive fuel.

1/ INTRODUCTION

This first evaluation program concerning the automotive use of natural gas fuel has been initiated by the Ministry of Transportation and Communications for the Province of Ontario (MTC). The engine testing done by the University of Toronto Engine Research Development Laboratory (ERDL) is supplemented by a chassis dynamometer test program carried out by MTC.

To initiate the research program, an engine representative of the types candidate for conversion was selected -- the FORD I-6 4.9 L (300 CID) is installed in a large number of light trucks and vans. The carburation systems selected for evaluation are also representative of the construction principles commercially available.

The test results can serve in the evaluation of the technical and economic impact of conversion to natural gas, as well as in the definition of the future research areas required for the best use of this alternative fuel.

2/ EXPERIMENTAL FACILITIES

2.1/ Test Engine

Make: FORD, Cleveland Engine Plant 1
Identification: BF 251 AB, code E
Number of cylinders: 6, in line, OHV
Serial number: C-00207-H-23-TG
Bore: 101.6 mm (4 in)
Stroke: 101.09 mm (3.98 in)
Displacement: 4.9 L (300 CID)
Compression ratio: 8.6:1
Camshaft: 'standard' 1981 (Overlap 48°; intake opens 18°; BTC duration 268°; exhaust opens 58°; BBC duration 268°; lift 0.40 in)
Carburettor: CARTER E1TE DA
A1E 15 NON2
Choke: EB 1672A
Distributor: 1F23
E1TE 12127 JA OPT
Centrifugal advance: 1000 rpm -- 0
1500 rpm -- 8°
3600 rpm -- 11°
Vacuum advance: 10 kPa (3 in Hg) -- 0
37 kPa (11 in Hg) -- 28°
(values in engine degrees ±3°)
Spark plugs: BSF 42 MOTORCRAFT
Gap: 0.045 in
Firing order: 153624
Emissions control system: calibration 1-51G as in 1981 F-100/150 vehicles (see Figure 1). The original catalytic converter and muffler are installed.
EGR valve: E1TE-9D 448-H2A 776
1E12AE
Air pump: COT E1TE-D2A
Electrical system: designed for engine dynamometer testing (see Figure 2).
Generator: 40A E1ZF 10346 AA
Voltage regulator: D9PF-10316-AB NEG

Electronic module: DURASPARK D8VE 12A199A2C

Fan: fixed blades, H D2OE-AB

Dynamometer coupling: standard flywheel, clutch and bellhousing for manual transmission

Engine support: 3 points (2 for engine, 1 for dynamometer, with original rubber vibration dampers), ensuring the horizontal position of the carburettor mounting surface on the intake manifold.

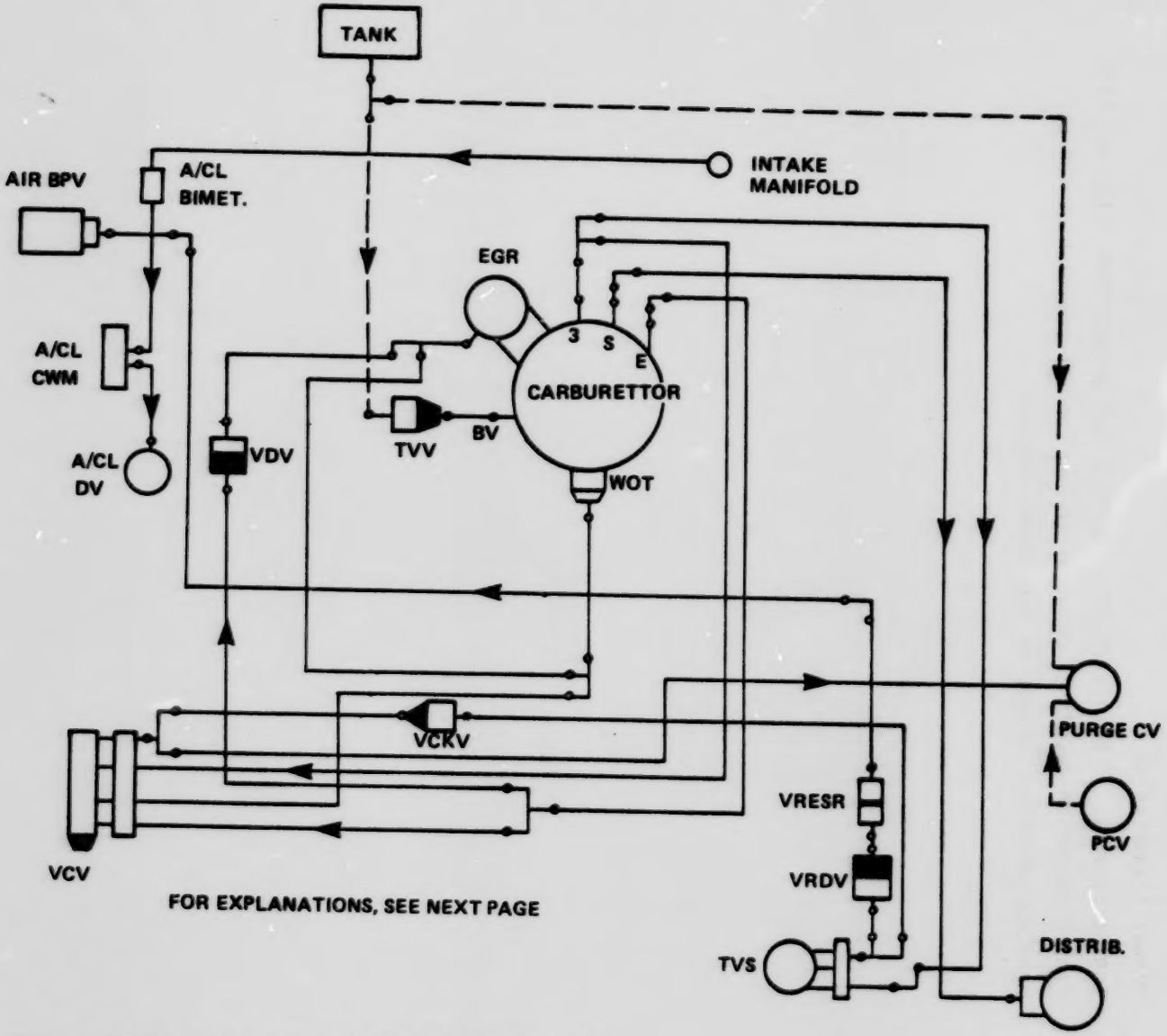

Figure 1/ Emissions Control System for Gasoline

Figure 1/ Emissions Control System for Gasoline (cont'd)

TVS = temperature vacuum switch
BPV = bypass valve
VRDV = vacuum retard delay valve
VCV = vacuum control valve
VCKV = vacuum check valve
VDV = vacuum differential delay valve
TVV = thermal vent valve
WOT = wide open throttle valve
VRESER = vacuum reservoir
A/CL = air cleaner
DV = duct and valve vacuum motor
CWM = cold weather modulator
EGR = exhaust recirculation valve
PCV = positive crank case ventilation valve

Inlet Air Temperature Control System: The air cleaner intake duct has a door controlled by a vacuum motor (A/CL DV), admitting cold air from outside or preheated air from a heat shroud around the exhaust manifold. The bimetal (A/CL BIMET.) and cold weather modulator (A/CL CWM) control the air temperature at which the vacuum is supplied to A/CL DV to activate the door for heated air.

Thermoactor Air Injection System: reduces the hydrocarbon and carbon monoxide content of exhaust by continuing the combustion in the exhaust manifold through injection of fresh air. The air is supplied by a mechanically driven pump and a check valve. At idle, the vacuum control of the bypass valve (AIR BPV) is routing the air supply out to atmosphere.

Evaporative Emission System: The fuel vapours from fuel tank and carburettor are stored into a carbon canister and under control of canister purge valve (PURGE CV) are drawn into the engine and burned.

Exhaust Gas Recirculation System: The vacuum controlled EGR valve reintroduces small amounts of exhaust gas into the combustion chamber, reducing the NO_x emission. At or near WOT, the EGR vacuum load control valve (WOT) is venting the EGR vacuum to atmosphere.

Vacuum Control Valve (VCV): controls vacuum during warm-up. Open two separate circuits of vacuum when engine coolant reaches the calibration temperature.

Temperature Vacuum Switch (TVS): same as VCV, bimetal activated.

Vacuum Delay Valve (VDV, VRDV): used for gradual application or release of vacuum, to improve emissions or driveability.

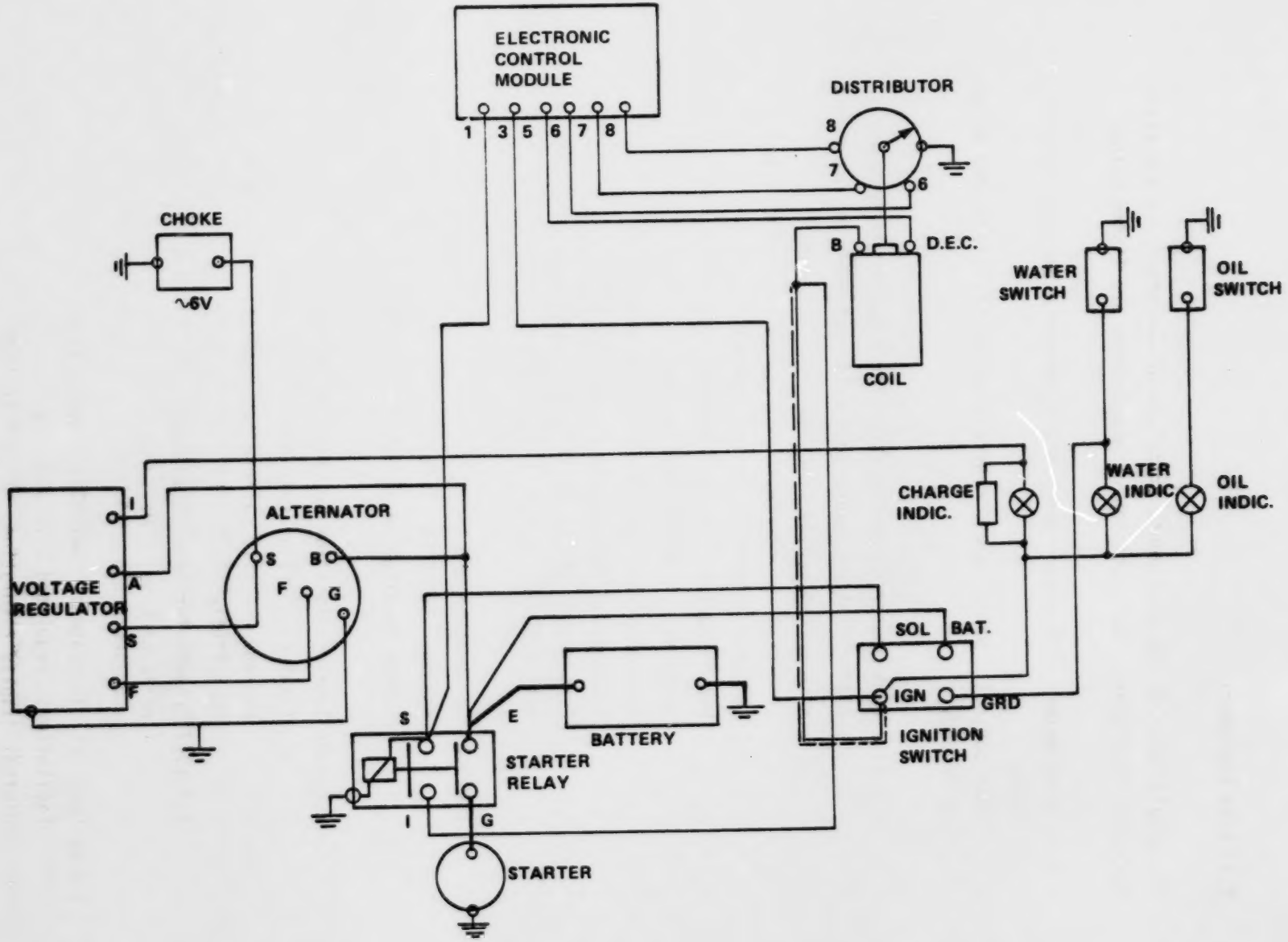

Figure 2/ Engine Electric System for Dynamometer Application

2.1/ Test Equipment

The manufacturer of the equipment, principle of operation and the characteristics determining the precision of measurement are listed below:

2.2.1/ Dynamometer: "Go-power' model 557 B, momentum exchange water brake.
Load control: water valve, controlling the filling of the dynamometer body.

2.2.1.1/ Dynamometer stator reaction force measuring system: electric strain-gauge load cell, actuated through a rod with self-aligning bearings.
Load cell: "Interface' -- "Sealed Super-Mini', model SSM-1000 (4482 N; 1000 lbf. range)
Non-linearity: ±0.05% rated output
Hysteresis: ±0.03% rate output
Non-repeatability: ±0.02% rated output
Compensated temperature range: 0-150°F
Temperature effect on zero or rated output: ±0.08% rated output/100°F

2.2.1.2/ Calibration arm
Length: 609.6 mm (2 ft)
Torque loading: 6.37 N.m (4.7 lb ft)

2.2.1.3/ Total calibration weight: 62.362 kg
Total calibration reading: 379.19 N.m
Average electric calibration reading: +252.9 N.m
Sensitivity: 0.04% FS

2.2.1.4/ Dynamometer speed transducer: 60 teeth gear and magnetic pick-up, 1 Hz/1 rpm

2.2.2/ Load cell indicator: "DAYTRONIC" model 3378
Excitation: regulated 2 V, 3.28 KHz
Digital display resolution: 1 part in 5000

2.2.3/ Speed indicator: "DAYTRONIC" model 3340; digital display characteristics as for 2.2.2

2.2.4/ Servo controlled throttle actuator system: 'Labeco' model 304. Angular position control and indication, adjustable for zero and WOT position of the carburettor shaft (indication 0 to 1000)

2.2.5/ Balance for fuel consumption measurement: "Mettler" model PK 36

Range: 0 to 30 000 g

Resolution: 0.1 g in 0 to 6000 g range ("Delta Range")
1 g in 6000 to 30 000 g range

Calibration: self, 16 000 g

Repeatability: 0.1 g in "Delta Range"
0.5 g

Linearity: ±0.1 g in "Delta Range"
±1 g

Temperature range: 0 to 40°C

2.2.6/ Temperature measurement: 'Doric Trendicator' series 400 A with 10 channels switching box and 'Hy-Cal Eng.' Thermocouples

Thermocouple designation: K (Chromel-Alumel)

Range: -200 to 1250°C

Accuracy of thermocouple: (ANSI MC 96.1-1975); ±2.2°C or 0.75% whichever is greater (in range 0 to 1250°C)

Accuracy of indicator: ±0.5°C

Junction: grounded

2.2.7/ Pressure measurement: "Doric Trendicator" model 400 A with 5 channels voltmeter and "Viatran" strain-gauge pressure transducers (amplifier included, 5 V DC FS output)

Transducer error band: ±0.4% FS

Temperature effect: ±2% FS/100°F

Internal calibration accuracy: ±1% FS

Frequency response: 7 Hz (model 223, 0-20 in H_2O)
2 kHz (model 218)

2.2.8/ Hydrocarbon analyzer: "Beckman" model 400
Measuring method: flame ionization detector (FID)
Ranges (as calibrated): 0-10, 0-25, 0-100, 0-250, 0-1000, 0-2500 and 0-10 000 parts per million (ppm) CH_4 equivalent
Reproductibility: 1% FS
Response speed: 90% within 0.5 s

2.2.9/ NO Analyzer : "Beckman" model 951
Measuring method: chemiluminiscence
Ranges: 0-10, 0-25, 0-100, 0-250, 0-1000, 0-2500 and 0-10 000 ppm
Sensitivity: 0.1 ppm on 10 ppm range
Linearity: ±1% FS
Precision: 0.5% FS
Dynamic response: <1 s

2.2.10/ O_2 Analyzer : "Beckman model OM-11
Measuring method: polarographic
Range: 0-25%
Accuracy: ±1% FS
Linearity: ±1.2% O_2
Response speed: 90% within 300 to 600 ms

2.2.11/ CO and CO_2 Analyzers : "Beckman" model 864
Measuring method: non-dispersive infrared (NDIR)
Ranges: 0-2 and 0-10% CO
0-20% CO_2
Precision: 1% FS
Noise: 1% FS
Zero or span drift: ±1% FS for 24 h
Response speed: adjustable, 90% in 0.5 to 26 s

2.2.12/ Exhaust sample conditioning system: "Beckman", with diaphragm compressor and air dryer

2.2.13/ Ignition timing: "Beckman" model IST 1560 ignition system tester

Range: 0-45° advance or retard

2.2.14/ Barometric pressure: "Eberbach" mercury barometer, 0.01 in divisions

2.2.15/ Water vapour pressure in atmosphereo: "Johnson" sling-psychrometer

3/ TEST PROCEDURE

The test procedure is based on the SAE Standard J 816b -- "Engine Test Code -- Spark Ignition and Diesel" and "GM Engine Test Code" -- VI edition, test 1 -- "Full throttle, as installed".

During the test, the net power as defined by the SAE Standard is measured, i.e., the engine is equipped with all the built-in accessories (fuel, oil and coolant pumps) and all the accessories necessary to perform its intended functions unaided (intake, exhaust, cooling, electric and emissions control systems). Specifically, this includes:

- air cleaner,
- fan,
- all standard emissions controls,
- muffler,
- alternator.

The parameter measured during the test are:

- engine rotational speed, N (rpm);
- torque, T (N.m);
- mass fuel consumption, W (g);
- inlet air temperature at filter (°C);
- inlet manifold air-fuel charge temperature (°C);
- average exhaust gas temperature (°C);
- exhaust gas temperature in the port of each cylinder (°C);
- spark advanced BTDC (°);
- manifold vacuum (kPa);
- lubrication oil pressure at filter (kPa);
- relative throttle position;
- barometric pressure, B (kPa);
- ambient temperature, t (°C);
- wet and dry bulb temperature (°C) for water vapour pressure in atmosphere, e (kPa);
- HC (methane-CH_4-equivalent) emission (ppm);
- NO emission (ppm);
- O_2 emission (%);
- CO emission (%);

- CO_2 emission (%).

The following parameters are calculated for correction of data at standard ambient conditions:

- brake power, observed (at test conditions), bp_t (kW);
- brake mean effective pressure, observed, $bmep_t$ (kPa);
- mechanical efficiency, n (%);
- friction power, observed, fp (kW);
- mass fuel consumption per hour, observed, F_t (g/h);
- brake specific fuel consumption, observed, $bsfc_t$ (g/kW.h);
- barometric pressure, corrected for dry air conditions, B_d (kPa);
- correction factor for standard atmospheric conditions, C_s;
- brake power, corrected bp_c (kW);
- torque, corrected T_c (N.m);
- brake mean effective pressure, corrected, $bmep_c$ (kPa).

The calculations are detailed in Appendix A.

The air-fuel ratio (A/F) is calculated from the emission components (HC, NO, O_2, CO, CO_2). The theoretical background of the method is presented in Appendix B. The various systems operations during the test are listed below:

a) Stabilize thermal regime of the engine.
b) Measure and record atmospheric conditions.
c) Load the engine at WOT (wide open throttle) to obtain the minimum stabilized speed and record the listed parameters for a two-minute period.
d) Decrease the load at the same speed at 2/3, 1/3 and minimum obtainable from maximum load and record the listed parameters for a two-minute period.
e) Repeat steps c) and d) each 500 rpm, up to 3500 rpm, to cover the peak obtainable power for the test engine.
f) Repeat steps a) to e) to check for consistency of data.

The baseline test with gasoline was conducted with the following settings:

- static timing 6° BTDC at maximum 800 rpm;
- 88± 6°C (190± 10°F) thermostatic control of cooling water outlet from

engine (SAE for dynamometer testing);
- all emissions controls in place and operational.

The evaluation tests with natural gas were conducted at the settings listed below:
- static timing 6° VTDC plus: "AUTOTRONIC dual curve ignition" module for AFS, IMPCO and BEAM carburation systems; "AUTOTRONIC dual curve ignition FORD replacement" module for CNG carburation system,

  (Both modules have been installed and calibrated by AFS and CNG technicians respectively, in accordance with their standard procedures. Centrifugal and vacuum advance unchanged.)

- cooling water temperature unchanged,
- emission controls unchanged and operational,
- spark plug model and gap unchanged.

The specifications for the carburation systems used are presented in Table 1 and the lay-out of installations in Figures 3 to 6.

Table 1/ Specifications for the CNG Carburation Systems

Carburation System	Pressure Regulator		Mixer		Comments
	Stages	Model	Principle	Model	
AFS	3	TARTARINI RP/76	flow nozzle	UM-2	
IMPCO	2*	EBS with EC1	air valve	CA 225	with air valve for NG DA-1793-RS
BEAM	2*	450B	venturi	C5-60-H6	with venturi for NG #310A-N48 (0.189" dia. holes) and modified place (0.375" dia. outer holes and 0.290" dia. inner hole).
CNG	3	LANDI RENZO GM 78 Size TN2/C	venturi	19-000154	

* First step of pressure reduction 3000/200 psi was added before the pressure regulator (MATHESON model 1H regulator).

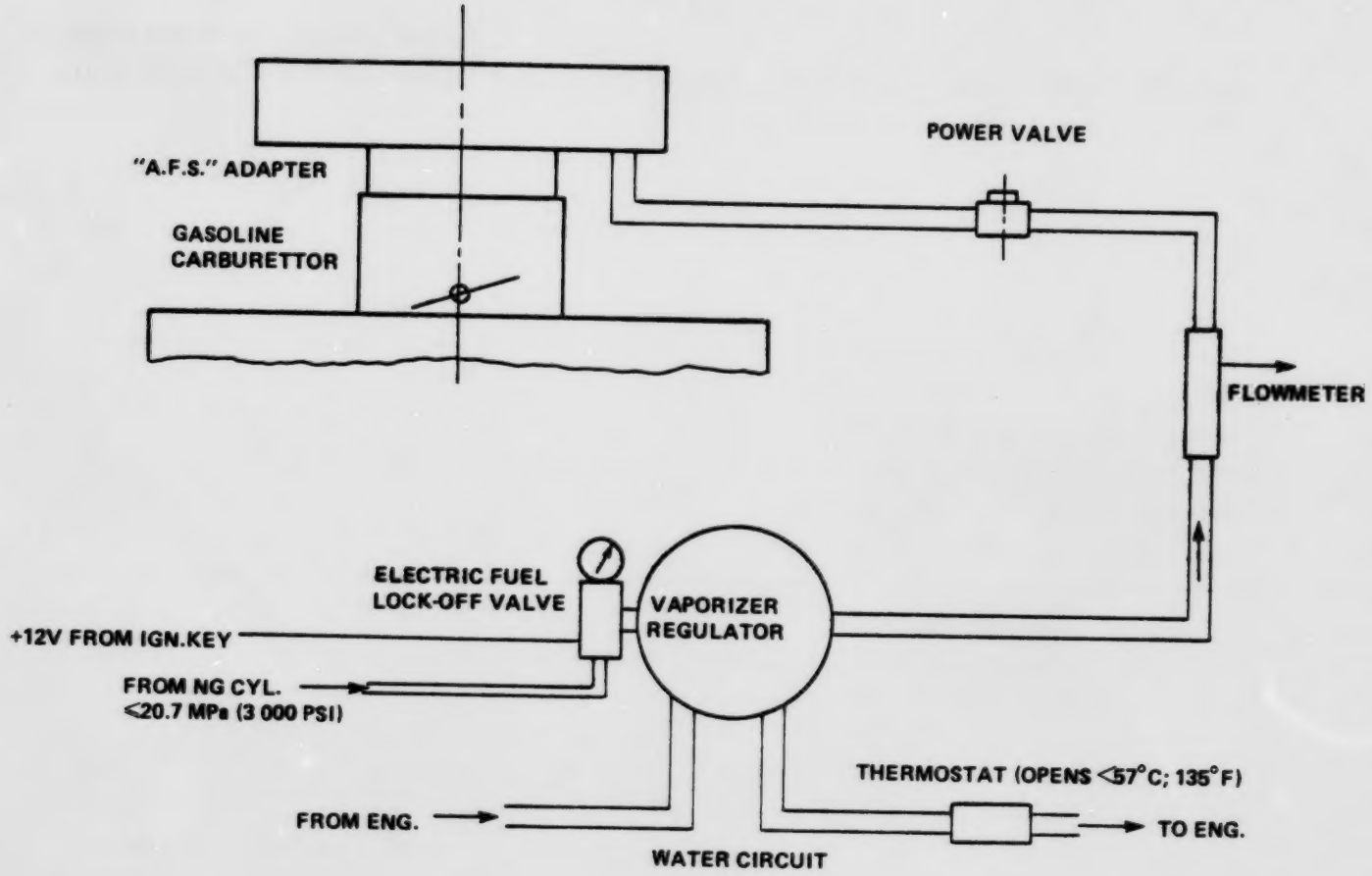

Figure 3/ AFS Natural Gas/Gasoline Carburation System Lay-Out

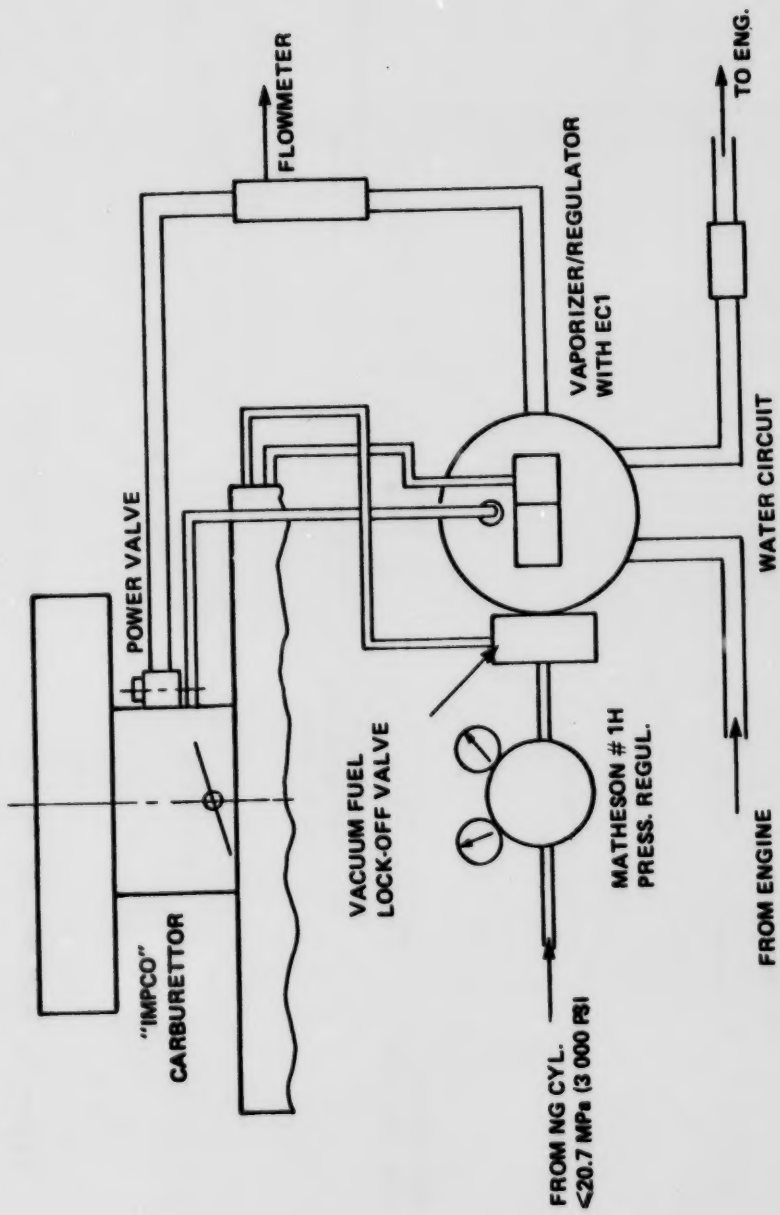

Figure 4/ IMPCO Natural Gas Carburation System Lay-Out

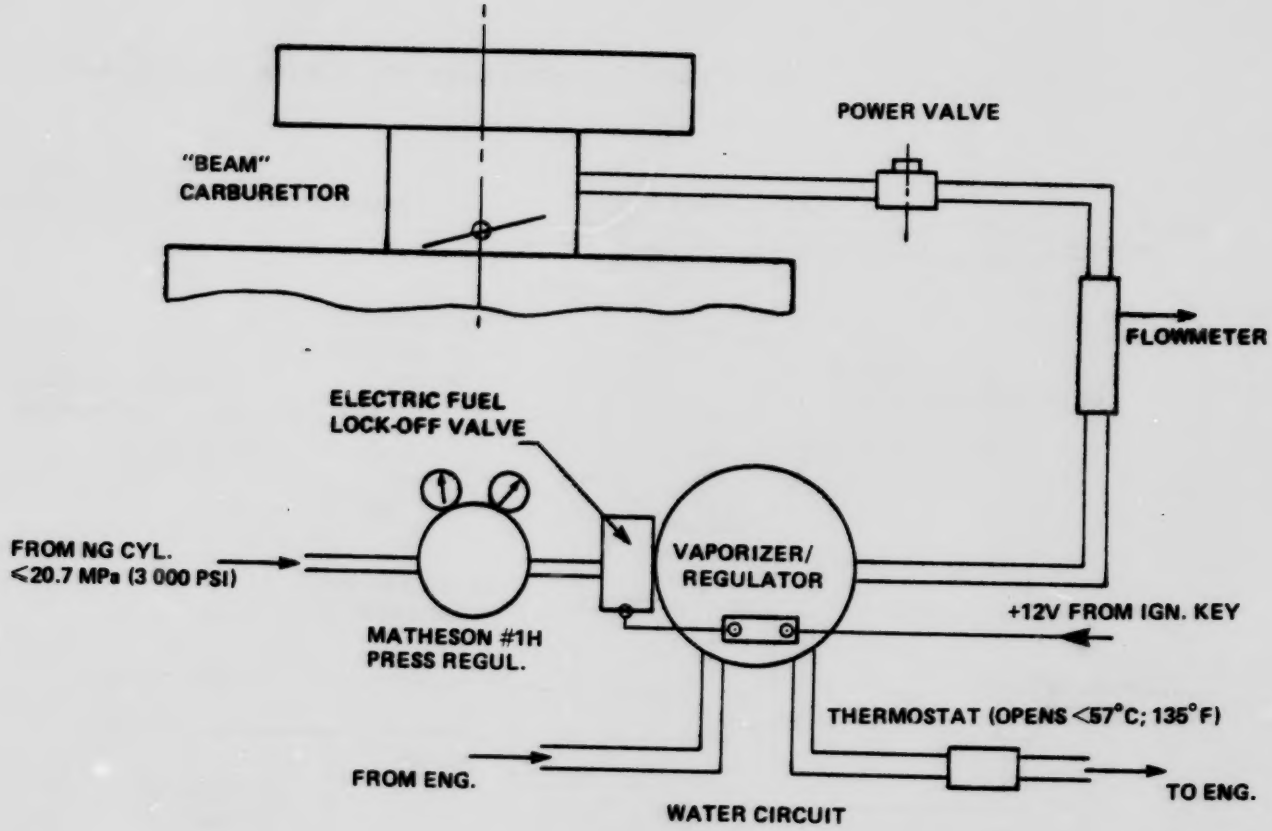

Figure 5/ BEAM Natural Gas Carburation System Lay-Out

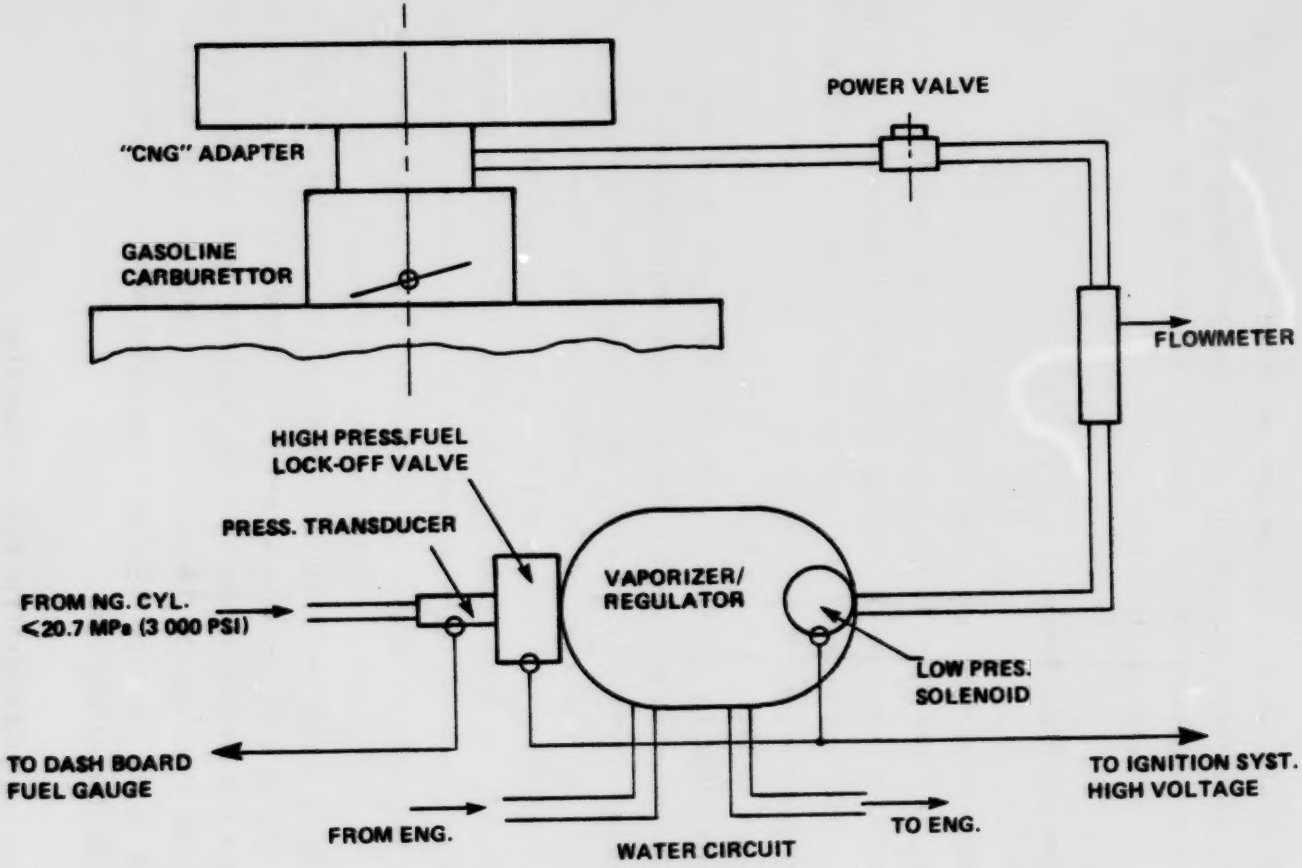

Figure 6/ CNG Natural Gas/Gasoline Carburation System Lay-Out

4/ TEST RESULTS AND INTERPRETATION

4.1/ Preliminary

The test results in this Section are presented in their final form, after reduction to standard atmospheric conditions and averaging of the runs. The raw data are available upon request. All data values represent the average of at least two test runs.

4.2/ Corrected Brake Power

The maximum corrected brake power obtained at wide open throttle (WOT) is presented in Table 2 and Figure 7. Figure 7 also shows the torque values from which the power was calculated. For ease of comparison, the percentage difference between each natural gas carburation system and the baseline gasoline system is also presented. The power developed with natural gas is 12.3 to 22.1% lower than for gasoline. The difference is far greater than for propane used on the same engine when the power was generally preserved and the maximum reduction registered was 5.9%. Such a marked reduction cannot be explained only by the differences in air-fuel ratio, but also requires to consider the significant difference in the burning speeds of the compared fuels. The natural gas, with lower burning speed, has less opportunity to burn completely in the cylinder, resulting in lower pressure and power developed, accompanied by lower exhaust temperatures, higher hydrocarbons emissions and reduced economy, as will be seen from the results for those parameters. The inlet charge temperatures are given in Table 3, showing a detrimental increase in charge temperatures for natural gas. The thermostat installed in the water heating circuit of the pressure regulator does not show any reduction of the inlet charge temperatures. The water-gas fuel heat exchangers of the pressure regulators, designed mainly for propane, seem to be too big for natural gas.

4.3/ Measured Brake Specific Fuel Consumption

The measured brake specific fuel consumption (BSFC) is presented in Tables 4 to 6 and the hourly consumption at no-load in Table 7, in mass terms. Figures 8 and 9 present those results in graphical form. The

mass consumption for natural gas varies between 19.8% lower and 38.6% higher than for gasoline.

To permit a direct comparison of the energy efficiencies of gasoline and natural gas carburation systems, the fuel consumption is shown in energy units in Tables 8 to 11. On this base, the natural gas has an efficiency varying between 12.6% higher and 51.2% lower than gasoline. The changes in energy efficiency for different speeds and loads are concentrated in Table 12 and Figure 10 in average terms and as maxima obtained for the best systems. The systems with a large area of mixing space fuel-air (e.g., AFS) present an improved economy. The venturi systems (e.g., BEAM, CNG), with relative smaller area of mixing are showing reduced fuel economy. And the proximity of air-fuel ratio and timing to the optimum values presents the same high importance as for any other fuel. The CNG system, for instance, is penalized by a far over-advanced timing. The immediate potential for improvement is demonstrated by the 10 to 20% difference in energy efficiency between the average values for all systems and the values obtained for the best systems.

For a more convenient comparison of the natural gas consumption in commercial terms, Tables 13 to 16 contain the values on a volume base.

4.4/ Manifold Vacuum

The values of the manifold vacuum are shown in Table 17 and Figure 11. Those values are grouped in clearly defined limits for different loads, permitting the implementation of air-fuel ratio control as function of load using the vacuum as feedback signal.

4.5/ Total Spark Advance

The total spark advance is presented in Table 18 and Figure 12. The ignition module used with the first three natural gas systems determines an increase of advance of 2 ÷ 14°, variable with load. The new model of ignition module used by CNG adds 3 ÷ 10° on top of the values for the previous one. From the optimization results in Section 5 will be seen that the timing determined by the first ignition module is over-advanced.

Adding to that 3 + 10° in the case of the module used by CNG enlarges the gap to the optimum values and results in higher fuel consumption.

4.6/ Relative Throttle Position

This indicator of the internal resistances to flow of different carburation systems is presented in Table 19.

4.7/ Exhaust Gas Temperatures

4.7.1/ Average Downstream Temperatures

The average temperatures in the exhaust system before the catalytic converter are recorded in Table 20 and Figure 13. For natural gas the temperatures are consistently lower, determined by the combustion characteristics of the fuel, timing and air-fuel ratio.

4.7.2/ Cylinder Temperatures

The distribution of exhaust temperatures in cylinder ports, as a measure of mixture distribution among cylinders, is presented in Tables 21 to 23 and Figures 14 to 16. As mentioned before, the temperatures are lower for natural gas, and the distribution of mixture follows very closely the pattern determined for gasoline.

4.8/ Emissions

4.8.1/ Hydrocarbons

The values for the hydrocarbons emission -- expressed as CH_4 (methane) -- are recorded in Table 24 and Figure 17. The values recorded for natural gas are far higher than for gasoline, due to the unsatisfactory combustion.

4.8.2/ Nitric Oxide

NO emission values are presented in Table 25 and Figure 18. This emission for natural gas follows closely the values for gasoline, indicating similarity of maximum temperatures in cylinders.

4.8.3/ Oxygen Excess

The excess oxygen left after combustion is recorded in Table 26 and Figure 19. The level of excess oxygen with natural gas is generally lower than for gasoline.

4.8.4/ Carbon Monoxide

CO emission results are shown in Table 27 and Figure 20. The incomplete combustion and the higher levels of CO emission increase with the speed for natural gas, overpassing the levels for gasoline.

4.9/ Air-Fuel Ratio

The air-fuel ratio, calculated from the emission values, is presented in Table 28. For a direct comparison of gasoline and natural gas systems, the equivalence air-fuel ratio is recorded in Table 29 and Figure 21.

Table 2/ Performance (Maximum Power) at WOT

$\frac{\text{(kW)}}{\text{\% vs. Gasoline}}$, Average Values

Carburation System	Engine Speed (rpm)				
	1600	2000	2500	3000	3500
Gasoline	54.41	67.02	78.64	90.64	90.69
AFS	46.93	58.59	66.93	73.46	73.55
	-13.75	-12.58	-14.89	-18.95	-18.90
IMPCO	43.76	55.67	66.52	73.25	73.90
	-19.57	-16.94	-15.41	-19.19	-18.51
BEAM	46.94	58.13	68.99	76.84	76.31
	-13.73	-13.26	-12.27	-15.23	-15.86
CNG	47.22	56.02	64.72	70.59	71.76
	-13.21	-16.41	-17.70	-22.12	-20.87

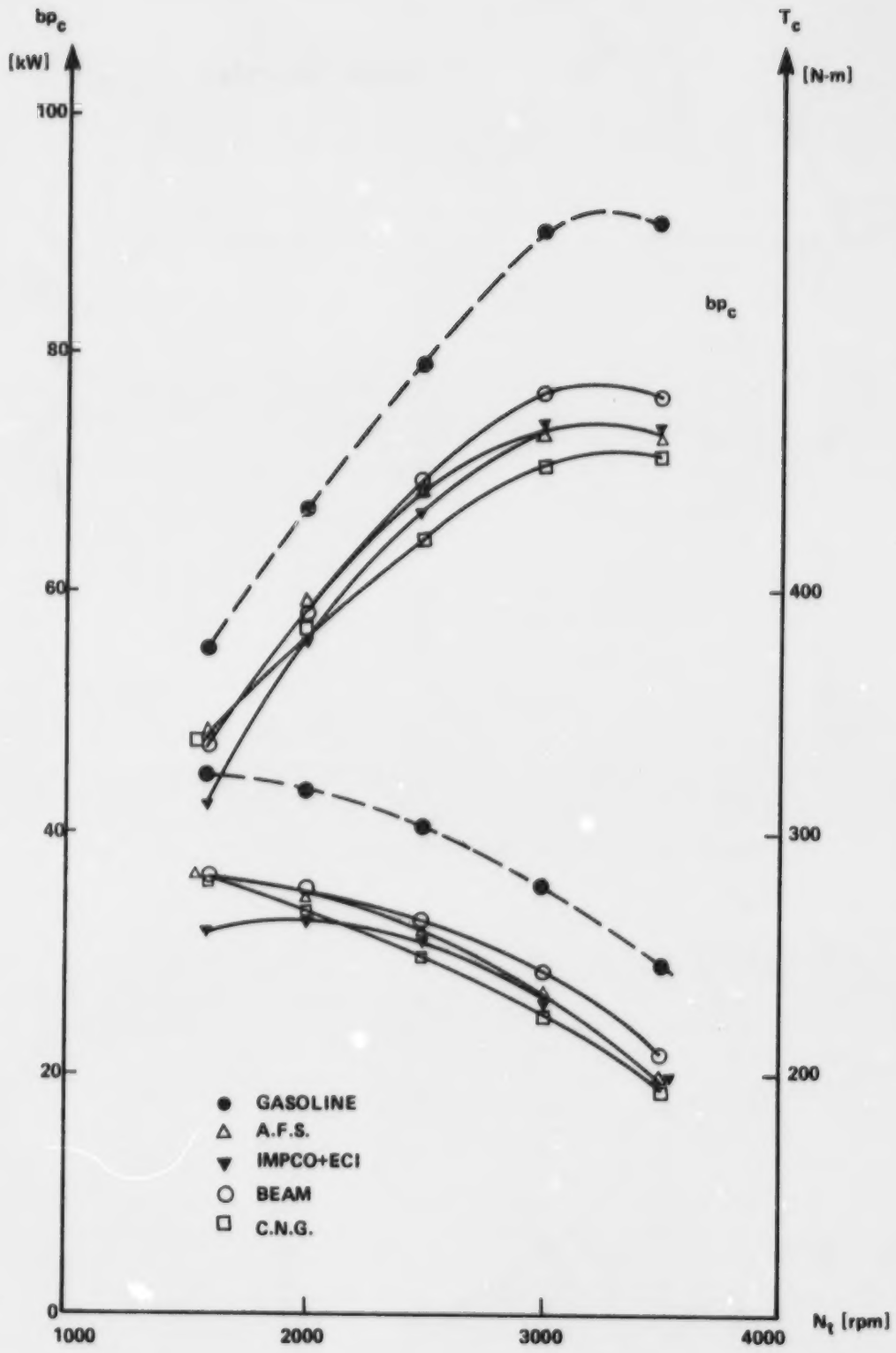

Figure 7/ Comparison of Power and Torque at Wide Open Throttle

Table 3/ Inlet Charge Temperature

(°C), Average Values

Load (%)	Carburation System	Engine Speed (rpm)				
		1600	2000	2500	3000	3500
100	Gasoline	17	25	26	26	28
	AFS	36	38	39	41	44
	IMPCO	40	40	39	40	40
	BEAM	37	41	39	39	37
	CNG	33	33	34	37	35
66	Gasoline	46	50	49	39	45
	AFS	74	77	77	81	81
	IMPCO	61	65	70	76	76
	BEAM	77	78	76	74	74
	CNG	68	68	70	73	77
33	Gasoline	51	57	56	56	55
	AFS	77	87	85	94	96
	IMPCO	78	80	81	81	77
	BEAM	80	84	90	89	87
	CNG	80	84	83	88	90
0	Gasoline	34	34	34	31	48
	AFS	49	50	69	75	97
	IMPCO	51	66	72	81	73
	BEAM	50	48	58	70	84
	CNG	53	63	72	85	88

Table 4/ BRAKE Specific Fuel Consumption

Mass Base -- 100% Load

$\frac{(g/kW.h)}{\%\ vs,\ Gasoline}$, Average Values

Carburation System	Engine Speed (rpm)				
	1600	2000	2500	3000	3500
Gasoline	274.03	266.02	284.87	295.48	301.82
AFS	243.05	237.94	261.62	299.63	327.72
	-11.31	-10.56	-8.19	+1.40	+8.58
IMPCO	262.21	262.40	291.60	324.82	352.90
	-4.31	-1.36	+2.33	+9.93	+16.92
BEAM	277.08	301.21	329.16	329.53	319.93
	+1.11	+13.23	+15.51	+11.52	+6.00
CNG	289.39	304.19	308.36	341.29	371.04
	+5.61	+14.35	+8.21	+15.50	+22.93

Natural gas composition:
- 95.5% methane (CH_4)
- 2.0% ethane (C_2H_6)
- 0.1% propane (C_3H_8)
- 0.01% butane (C_4H_{10})
- 1.8% nitrogen (N_2)
- 0.34% carbon dioxide (CO_2)

Results in a density of 0.6899 g/L @ 21°C, 101 kPa.

Table 5/ Brake Specific Fuel Consumption

Mass Base -- 66% Load

$\frac{(g/kW.h)}{\%\ vs.\ Gasoline}$, Average Values

Carburation System	Engine Speed (rpm)				
	1600	2000	2500	3000	3500
Gasoline	291.15	281.78	298.13	311.07	322.42
AFS	255.93	264.47	278.53	306.66	345.86
	-12.10	-6.14	-6.57	-1.42	+7.27
IMPCO	259.54	272.25	299.52	332.41	397.91
	-10.86	-3.38	+0.47	+6.86	+23.41
BEAM	275.50	287.30	303.50	347.40	377.90
	-5.38	+1.95	+1.80	+11.68	+17.21
CNG	321.64	322.25	339.99	363.77	415.34
	+10.47	+14.36	+14.04	+16.94	+28.82

Table 6/ Brake Specific Fuel Consumption

Mass Base -- 33% Load

$\frac{(g/kW.h)}{\%\ vs.\ Gasoline}$, Average Values

Carburation System	Engine Speed (rpm)				
	1600	2000	2500	3000	3500
Gasoline	340.97	342.07	362.58	376.14	425.15
AFS	306.93	327.90	357.97	407.52	468.68
	-9.98	-4.14	-1.27	+8.34	+10.24
IMPCO	371.88	373.80	418.32	471.55	514.00
	+9.06	+9.28	+15.37	+25.37	+20.90
BEAM	373.50	373.80	414.45	492.10	542.10
	+9.54	+9.28	+14.31	+30.83	+27.51
CNG	406.93	408.39	459.50	494.14	589.44
	+19.34	+19.39	+26.73	+31.38	+38.64

Table 7/ Brake Specific Fuel Consumption

Mass Base -- 0% Load

$\frac{(g/kW.h)}{\%\ vs.\ Gasoline}$, Average Values

Carburation System	Engine Speed (rpm)				
	1600	2000	2500	3000	3500
Gasoline	2 878	3 720	5 150	6 130	7 970
AFS	2 307	3 181	4 190	5 637	7 204
	-19.84	-14.49	-18.64	-8.04	-9.61
IMPCO	3 029	4 025	5 328	7 041	9 195
	-5.25	+8.20	+3.46	+14.86	+15.37
BEAM	3 162	3 849	5 139	7 345	9 348
	+9.87	+3.47	-0.21	+19.82	+17.29
CNG	3 375	4 080	5 310	6 915	9 300
	+17.27	+9.68	+3.11	+12.81	+16.69

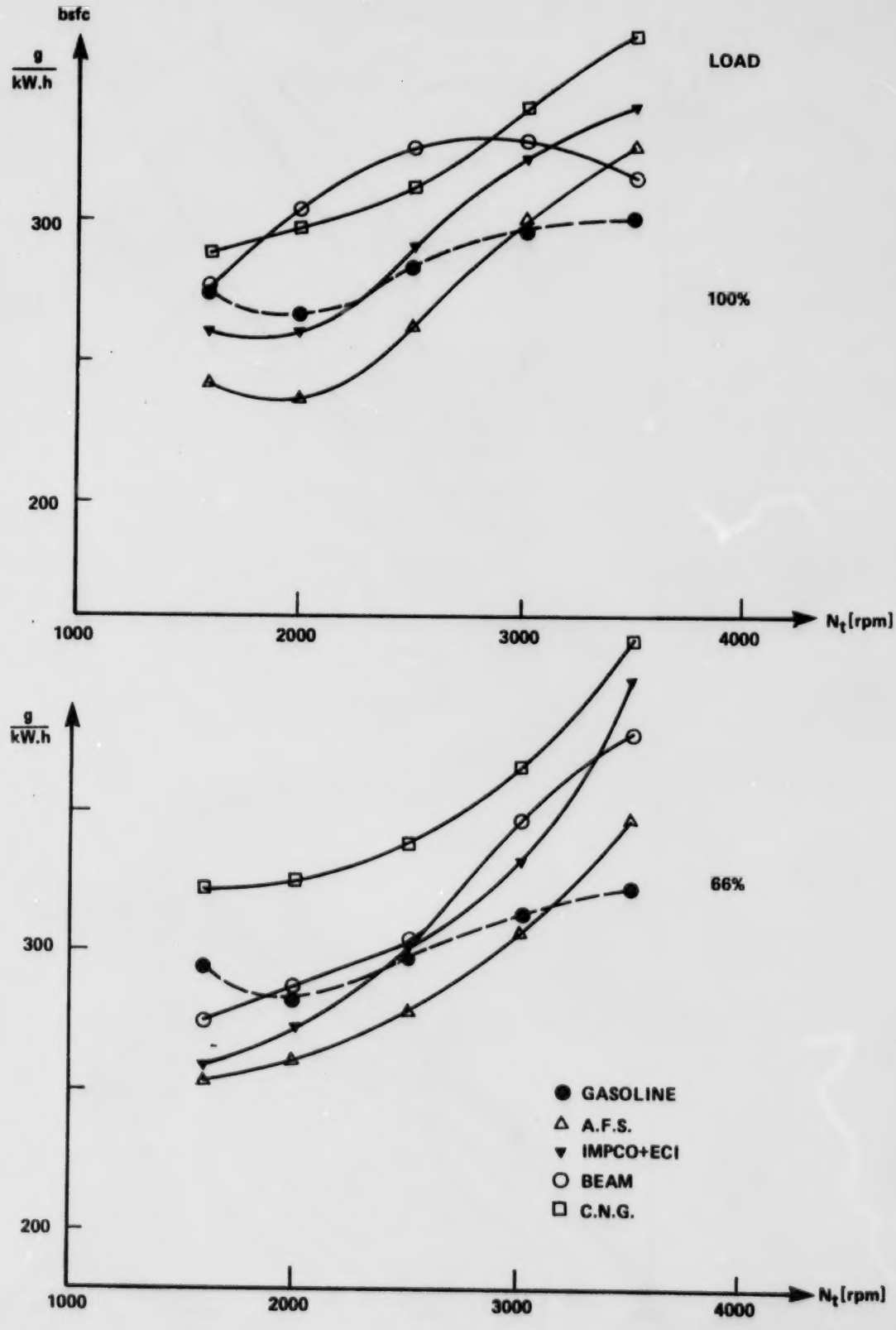

Figure 8/ Comparison of Brake Specific Fuel Consumption -- Mass Base

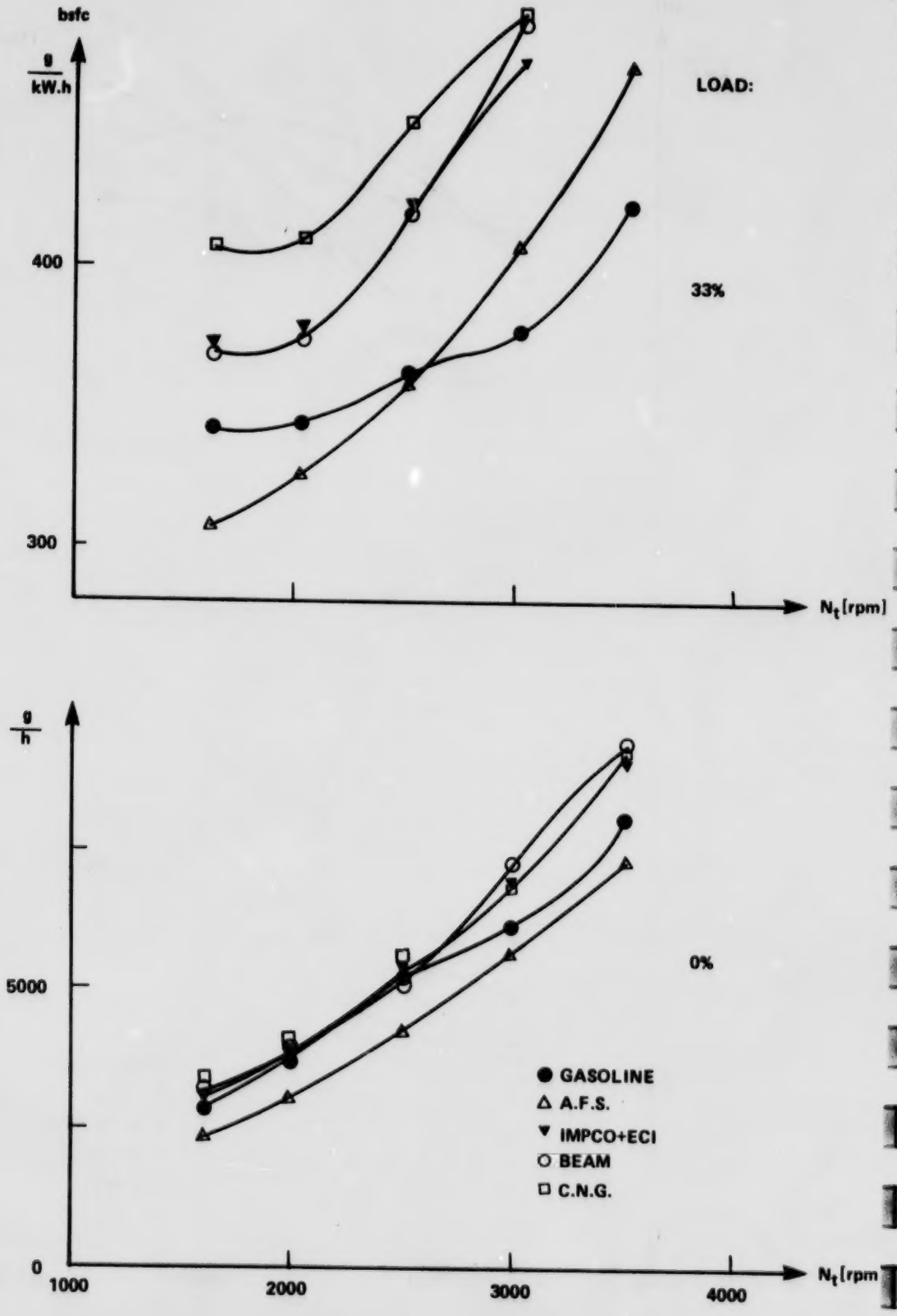

Figure 9/ Comparison of Brake Specific Fuel Consumption -- Mass Base (Cont'd.)

Table 8/ Brake Specific Fuel Consumption

Energy Base -- 100% Load

$\frac{\text{(kJ/kW.h)}}{\text{\% vs. Gasoline}}$, Average Values

Carburation System	Engine Speed (rpm)				
	1600	2000	2500	3000	3500
Gasoline	12 058	11 706	12 540	13 002	13 281
AFS	11 663	11 418	12 554	14 378	15 726
	-3.28	-2.46	+0.11	+10.58	+18.41
IMPCO	12 582	12 592	13 993	15 587	16 935
	+4.35	+7.57	+11.59	+19.88	+27.51
BEAM	13 296	14 454	15 795	15 813	15 352
	+10.27	+23.48	+25.96	+21.62	+15.59
CNG	13 887	14 597	14 797	16 377	17 805
	+15.17	+24.70	+18.00	+25.96	+34.06

Net heat of combustion @ 25°C, constant pressure:

Gasoline: 44 003 kJ/kg

Natural Gas: 47 986 kJ/kg for the composition in Table 4

(50 010 kJ/kg for CH_4

48 576 kJ/kg for C_2H_6)

Table 9/ Brake Specific Fuel Consumption

Energy Base -- 66% Load

$\frac{\text{(kJ/kW.h)}}{\text{\% vs. Gasoline}}$, Average Values

Carburation System	Engine Speed (rpm)				
	1600	2000	2500	3000	3500
Gasoline	12 811	12 399	13 119	13 680	14 187
AFS	12 281	12 691	13 366	14 715	16 596
	-4.14	+2.36	+1.88	+7.57	+16.98
IMPCO	12 454	13 064	14 373	15 951	19 094
	-2.79	+5.36	+9.56	+16.60	+34.59
BEAM	13 220	13 786	14 564	16 670	18 134
	+3.19	+11.19	+11.01	+21.86	+27.82
CNG	15 434	15 463	16 315	17 456	19 931
	+20.47	+24.71	+24.36	+27.60	+40.49

Table 10/ Brake Specific Fuel Consumption

Energy Base -- 33% Load

$\frac{\text{(kJ/kW.h)}}{\text{\% vs. Gasoline}}$, Average Values

Carburation System	Engine Speed (rpm)				
	1600	2000	2500	3000	3500
Gasoline	15 004	15 052	15 955	16 551	18 708
AFS	14 728	15 735	17 178	19 555	22 490
	-1.84	+4.54	+7.67	+18.15	+20.22
IMPCO	17 845	17 937	20 074	22 628	24 664
	+16.54	+19.17	+25.82	+36.72	+31.84
BEAM	17 923	17 937	19 888	23 614	26 013
	+19.45	+19.17	+24.65	+42.67	+39.05
CNG	19 527	19 597	22 050	23 712	28 285
	+30.15	+30.20	+38.20	+43.27	+51.19

Table 11/ Brake Specific Fuel Consumption

Energy Base -- 0% Load

$\frac{\text{(kJ/kW.h)}}{\text{\% vs. Gasoline}}$, Average Values

Carburation System	Engine Speed (rpm)				
	1600	2000	2500	3000	3500
Gasoline	126 641	163 691	226 615	269 738	350 704
AFS	110 704	152 643	201 061	270 497	345 691
	-12.58	-6.75	-11.28	+0.28	-1.43
IMPCO	145 350	193 144	255 669	337 869	441 231
	+14.77	+17.99	+12.82	+25.26	+25.81
BEAM	151 732	184 698	246 600	362 457	448 573
	+19.81	+12.83	+8.82	+30.67	+27.91
CNG	161 953	195 783	254 806	331 823	446 270
	+27.88	+19.61	+12.44	+23.02	+27.25

Table 12/ Changes in Energy Efficiency

(%) for the Natural Gas Carburation Systems vs. Gasoline

Load (%)	Carburation System	Engine Speed (rpm)					Average All Speeds
		1600	2000	2500	3000	3500	
100	-	-6.63	-13.32	-14.29	-19.51	-23.89	-15.52
66	-	-4.18	-10.91	-11.70	-18.41	-29.97	-15.03
33	-	-16.01	-18.27	-24.01	-35.20	-35.58	-25.81
0	-	-12.47	-10.92	-5.70	-19.81	-19.89	-13.75

Maximum for the Best Systems

100	AFS	+3.28	+2.46	-0.11	-10.58		-4.10
	BEAM					-15.59	-4.10
66	AFS	+4.14	-2.36	-1.88	-7.57	-16.98	-4.93
33	AFS	+1.84	-4.54	-7.67	-18.15	-20.22	-9.75
0	AFS	+12.58	+6.75	+11.28	-0.28	+1.43	+6.35

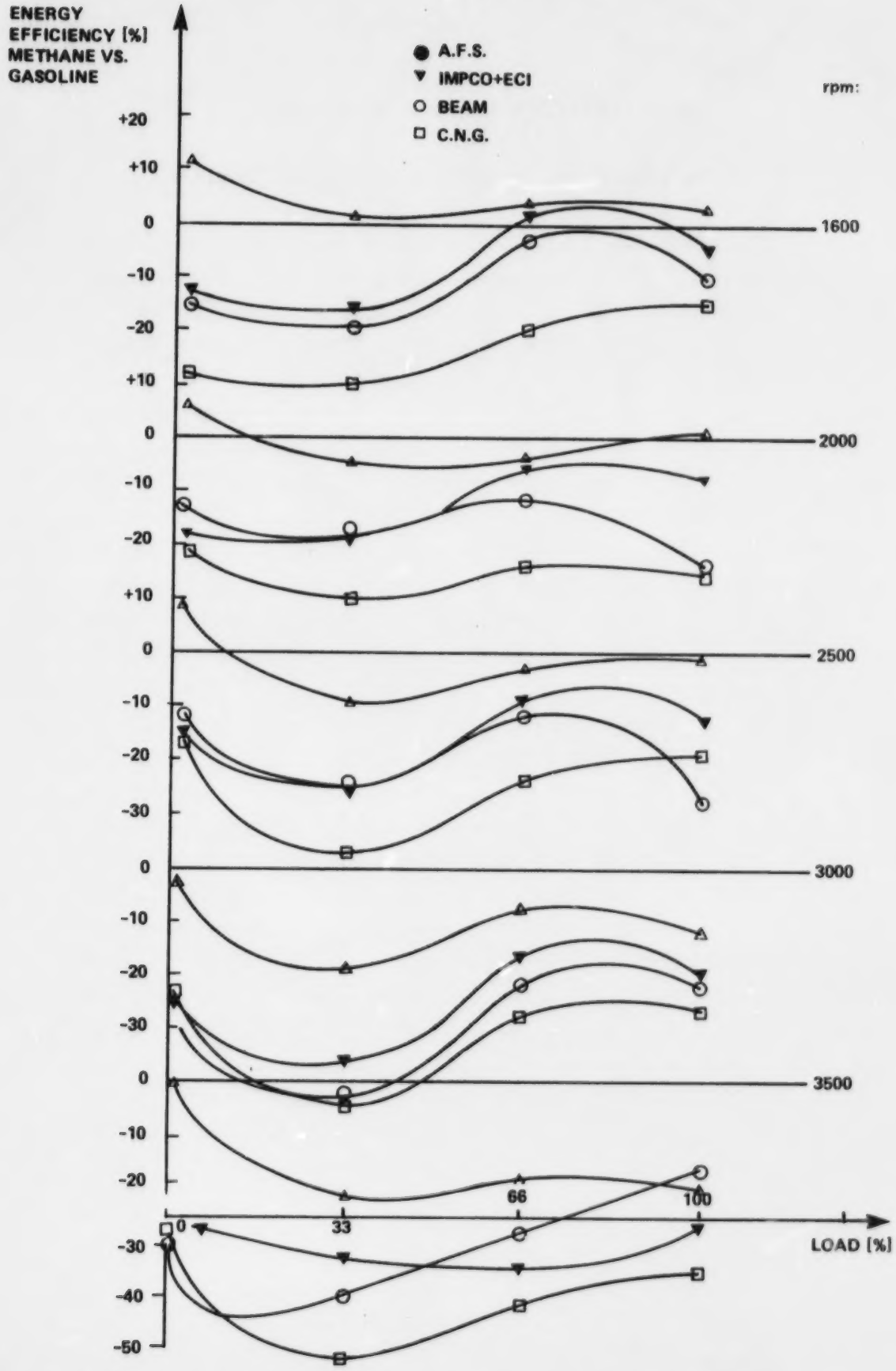

Figure 10/ Energy Efficiency of Natural Gas Carburation System vs. Gasoline

Table 13/ Brake Specific Fuel Consumption

Volume Base -- 100% Load

$\frac{(m^3/kW.h)}{\%\ vs.\ AFS}$, @ 21°C, 101 kPa, Average Values

Carburation System	Engine Speed (rpm)				
	1600	2000	2500	3000	3500
AFS	0.352	0.345	0.379	0.434	0.475
IMPCO	0.380	0.380	0.423	0.471	0.512
	+7.95	+10.14	+11.61	+8.52	+7.79
BEAM	0.402	0.437	0.477	0.478	0.464
	+14.20	+26.67	+25.86	+10.14	-2.32
CNG	0.419	0.441	0.447	0.495	0.538
	+19.03	+27.83	+17.94	+14.06	+13.26

Natural gas (composition in Table 4): 1.4495 m^3/kg @ 21°C, 101 kPa.

Table 14/ Brake Specific Fuel Consumption

Volume Base -- 66% Load

$\frac{(m^3/kW.h)}{\%\ vs.\ AFS}$, @ 21°C, 101 kPa, Average Values

Carburation System	Engine Speed (rpm)				
	1600	2000	2500	3000	3500
AFS	0.371	0.383	0.404	0.445	0.501
IMPCO	0.376	0.395	0.434	0.482	0.577
	+1.35	+3.13	+7.43	+8.31	+15.17
BEAM	0.399	0.416	0.440	0.504	0.548
	+7.55	+8.62	+8.91	+13.26	+9.38
CNG	0.466	0.467	0.493	0.527	0.602
	+25.61	+21.93	+22.03	+18.43	+20.16

Table 15/ Brake Specific Fuel Consumption

Volume Base -- 33% Load

$\frac{(m^3/kW.h)}{\%\ vs.\ AFS}$, @ 21°C, 101 kPa, Average Values

Carburation System	Engine Speed (rpm)				
	1600	2000	2500	3000	3500
AFS	0.445	0.475	0.519	0.591	0.679
IMPCO	0.539	0.542	0.606	0.684	0.745
	+21.12	+14.11	+16.76	+15.74	+9.72
BEAM	0.541	0.542	0.601	0.713	0.786
	+21.57	+14.11	+15.80	+20.64	+15.76
CNG	0.590	0.592	0.666	0.716	0.854
	+32.58	+24.63	+28.32	+21.15	+25.77

Table 16/ Brake Specific Fuel Consumption

Volume Base -- 0% Load

$\frac{(m^3/kW.h)}{\%\ vs.\ AFS}$, @ 21°C, 101 kPa, Average Values

Carburation System	Engine Speed (rpm)				
	1600	2000	2500	3000	3500
AFS	3.344	4.611	6.073	8.171	10.442
IMPCO	4.391 +31.31	5.834 +26.52	7.723 +27.17	10.206 +24.91	13.328 +27.64
BEAM	4.583 +37.05	5.579 +20.99	7.449 +22.66	10.647 +30.30	13.550 +29.76
CNG	4.892 +46.29	5.914 +28.26	7.697 +26.74	10.023 +22.67	13.480 +29.09

Table 17/ Manifold Vacuum

(kPa), Average Values

Load (%)	Carburation System	Engine Speed (rpm)				
		1600	2000	2500	3000	3500
100	Gasoline	3.36	5.01	7.70	11.12	13.55
	AFS	4.09	6.26	9.83	13.66	17.22
	IMPCO	3.00	4.10	5.40	7.40	8.85
	BEAM	1.81	2.84	4.55	6.36	7.91
	CNG	2.94	4.33	6.70	9.70	12.35
66	Gasoline	15.61	15.67	15.67	15.82	16.54
	AFS	15.10	16.75	23.53	23.69	24.90
	IMPCO	14.15	14.50	15.45	18.60	19.65
	BEAM	15.90	16.00	17.00	17.40	19.00
	CNG	14.80	15.80	19.10	19.20	21.75
33	Gasoline	44.57	44.41	44.46	43.79	43.12
	AFS	44.16	45.51	49.60	49.34	49.08
	IMPCO	34.85	37.65	40.05	40.70	40.60
	BEAM	41.80	42.90	43.90	44.10	43.70
	CNG	41.45	42.60	44.20	43.40	43.15
0	Gasoline	61.01	69.02	76.67	76.26	71.09
	AFS	63.71	72.35	74.41	73.23	69.60
	IMPCO	62.75	60.90	59.90	58.90	56.20
	BEAM	68.60	70.80	67.90	64.10	59.10
	CNG	66.50	68.50	66.40	63.80	59.80

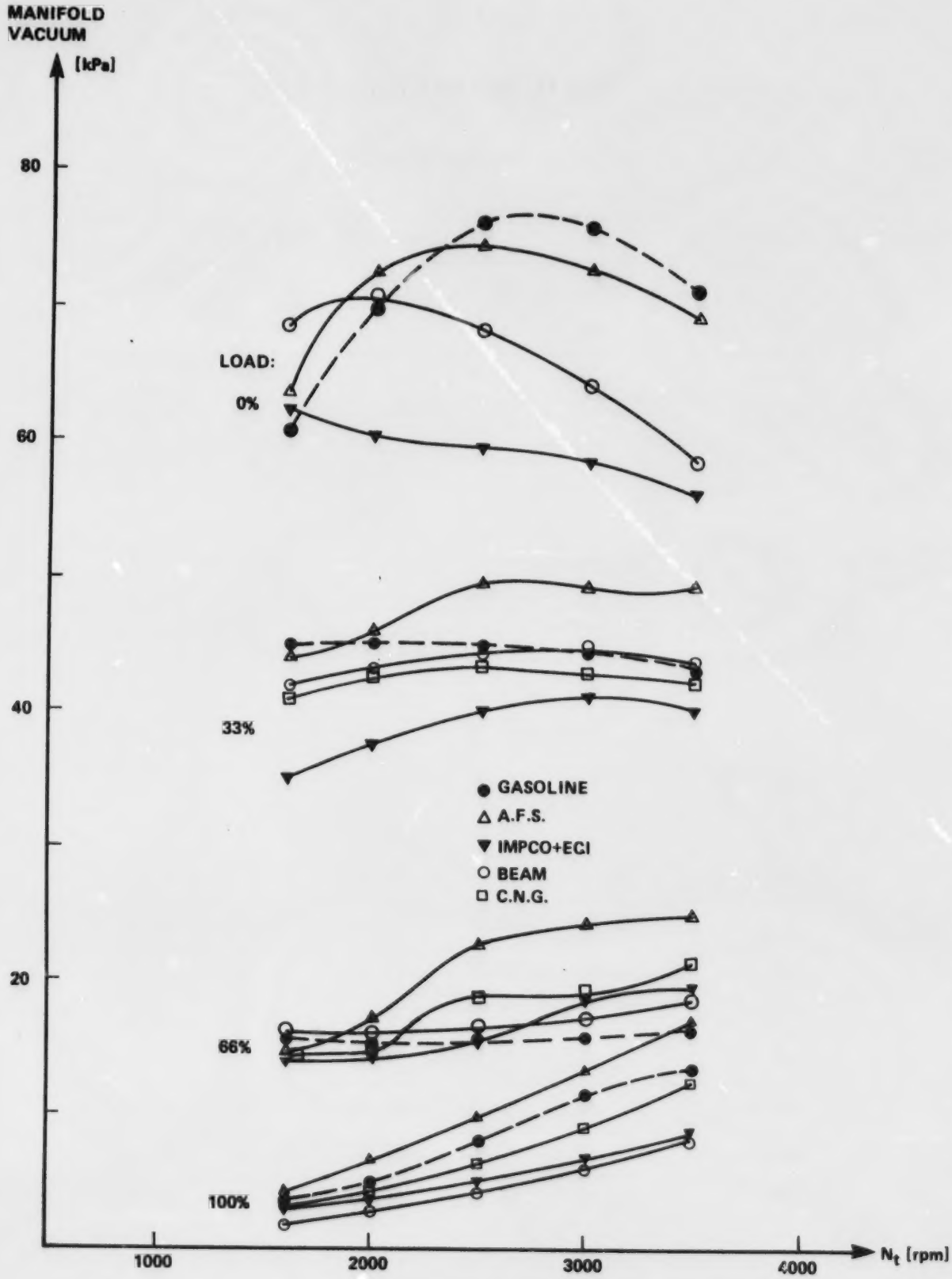

Figure 11/ Comparison of Vacuum Manifold

Table 18/ Total Spark Advance

(°), Average Values

Load (%)	Carburation System	Engine Speed (rpm)				
		1600	2000	2500	3000	3500
100	Gasoline	13.0	16.0	16.3	19.5	22.0
	AFS	22.5	25.5	27.0	29.5	31.8
	IMPCO	22.5	25.0	27.0	30.0	32.0
	BEAM	22.5	25.0	27.0	30.0	32.0
	CNG	30.5	33.0	32.0	33.3	36.5
66	Gasoline	19.5	23.0	23.5	25.0	25.3
	AFS	29.5	35.0	40.0	38.5	39.0
	IMPCO	30.0	35.0	39.0	39.0	39.0
	BEAM	30.0	35.0	39.0	39.0	39.0
	CNG	36.5	41.0	44.0	43.0	45.5
33	Gasoline	39.0	42.5	43.5	43.0	43.5
	AFS	46.0	46.3	46.0	46.0	46.0
	IMPCO	46.0	46.0	46.0	46.0	46.0
	BEAM	46.0	46.0	46.0	46.0	46.0
	CNG	53.0	55.0	55.0	55.0	55.0
0	Gasoline	38.8	41.0	43.0	44.0	44.0
	AFS	46.5	46.3	46.3	46.0	46.0
	IMPCO	46.0	46.0	46.0	46.0	46.0
	BEAM	46.0	46.0	46.0	46.0	46.0
	CNG	32.5	51.00	55.0	55.0	55.0

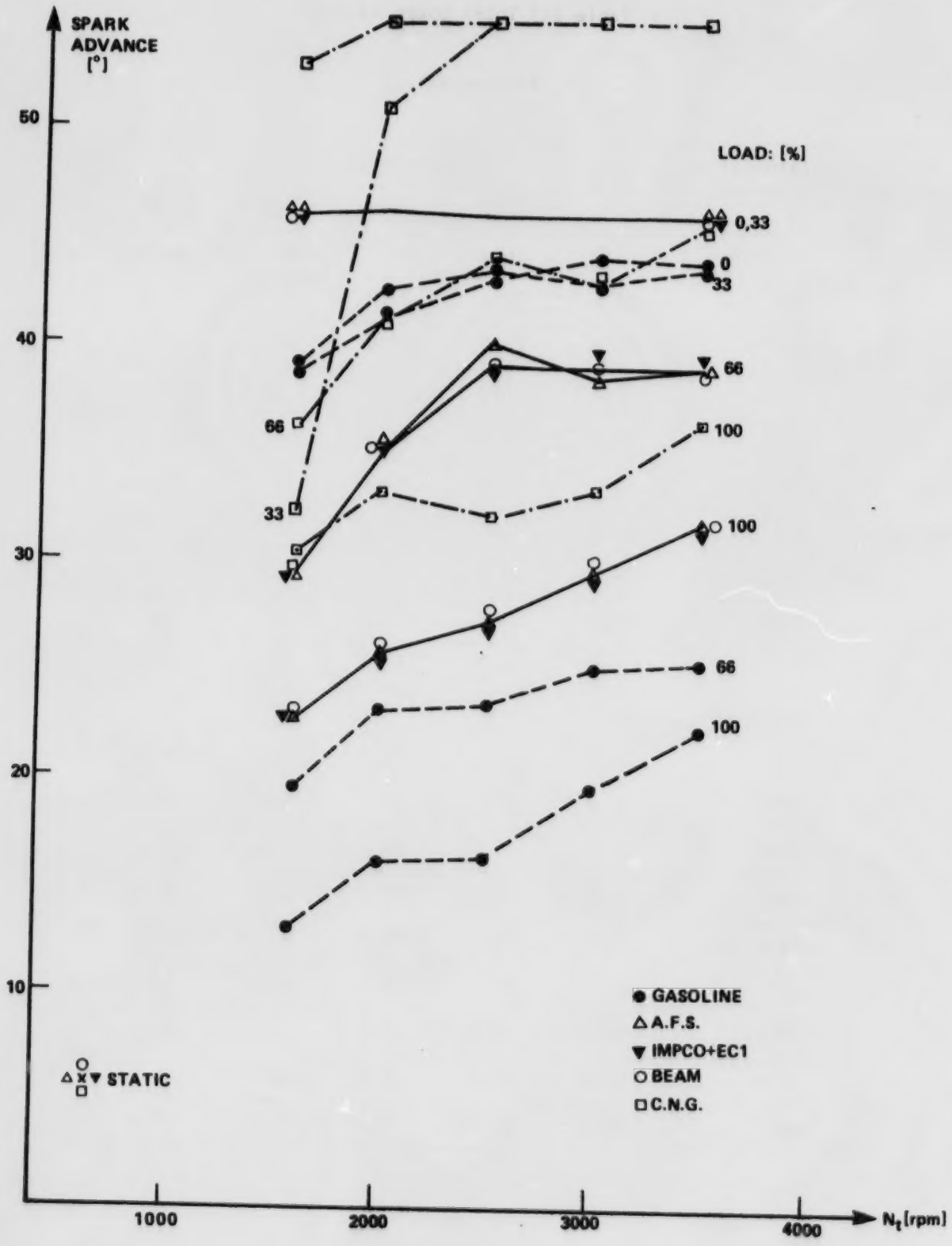

Figure 12/ Comparison of Total Spark Advance Curves

Table 19/ Throttle Position

(0-1000 for idle -- WOT), Average Values

Load (%)	Carburation System	Engine Speed (rpm)				
		1600	2000	2500	3000	3500
66	Gasoline	300	363	442	535	556
	AFS	301	346	373	418	453
	IMPCO	322	376	428	437	463
	BEAM	296	342	397	448	469
	CNG	387	440	475	527	547
33	Gasoline	145	183	229	276	307
	AFS	141	176	205	242	273
	IMPCO	187	215	249	277	308
	BEAM	181	207	240	275	300
	CNG	238	241	310	348	379
0	Gasoline	52	73	105	138	178
	AFS	63	86	116	152	187
	IMPCO	105	135	167	196	234
	BEAM	115	139	168	200	233
	CNG	167	187	219	252	289

Table 20/ Exhaust Gas Temperatures

(°C), Average Values

Load (%)	Carburation System	Engine Speed (rpm)				
		1600	2000	2500	3000	3500
100	Gasoline	702	747	792	812	838
	AFS	642	682	725	747	761
	IMPCO	615	667	708	733	778
	BEAM	595	660	696	750	769
	CNG	624	655	706	734	772
66	Gasoline	631	683	730	752	785
	AFS	575	626	660	694	718
	IMPCO	551	601	653	696	723
	BEAM	551	608	651	686	709
	CNG	588	630	649	700	722
33	Gasoline	529	576	606	647	666
	AFS	480	538	577	630	660
	IMPCO	483	524	560	618	645
	BEAM	493	549	596	636	654
	CNG	517	559	592	628	664
0	Gasoline	413	449	520	580	624
	AFS	371	419	498	548	573
	IMPCO	410	469	510	563	561
	BEAM	393	439	498	553	589
	CNG	443	482	522	576	607

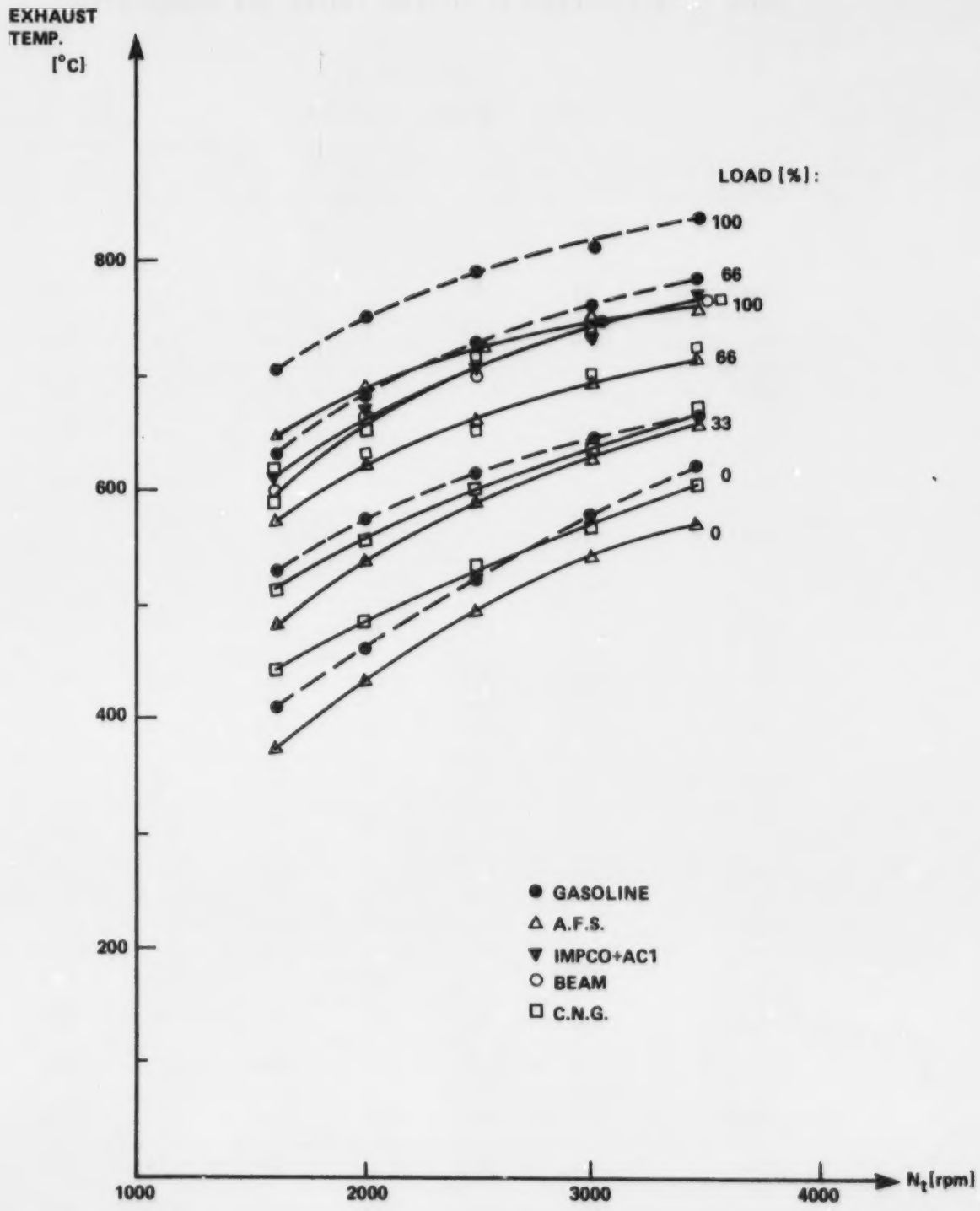

Figure 13/ Comparison of Exhaust Gas Temperatures

Table 21/ Distribution of Cylinder Exhaust Gas Temperatures

(°C), Average Values
Engine Speed: 1600 rpm

Load (%)	Carburation System	Cylinder Number					
		1	2	3	4	5	6
100	Gasoline	723	746	750	802	754	740
	AFS	686	697	696	748	706	709
	IMPCO	652	672	673	698	658	659
	BEAM	633	652	641	687	656	659
	CNG	670	686	671	703	656	662
66	Gasoline	690	700	699	745	722	730
	AFS	636	648	646	690	666	671
	IMPCO	576	599	599	630	605	611
	BEAM	608	629	623	657	635	642
	CNG	617	642	644	669	642	639
33	Gasoline	627	637	622	659	660	665
	AFS	585	592	576	612	614	616
	IMPCO	535	560	544	567	568	570
	BEAM	579	602	589	606	607	612
	CNG	579	604	595	611	610	612
0	Gasoline	553	589	556	591	592	605
	AFS	473	500	472	506	515	521
	IMPCO	501	528	489	523	537	555
	BEAM	476	510	500	526	534	539
	CNG	552	591	574	591	603	605

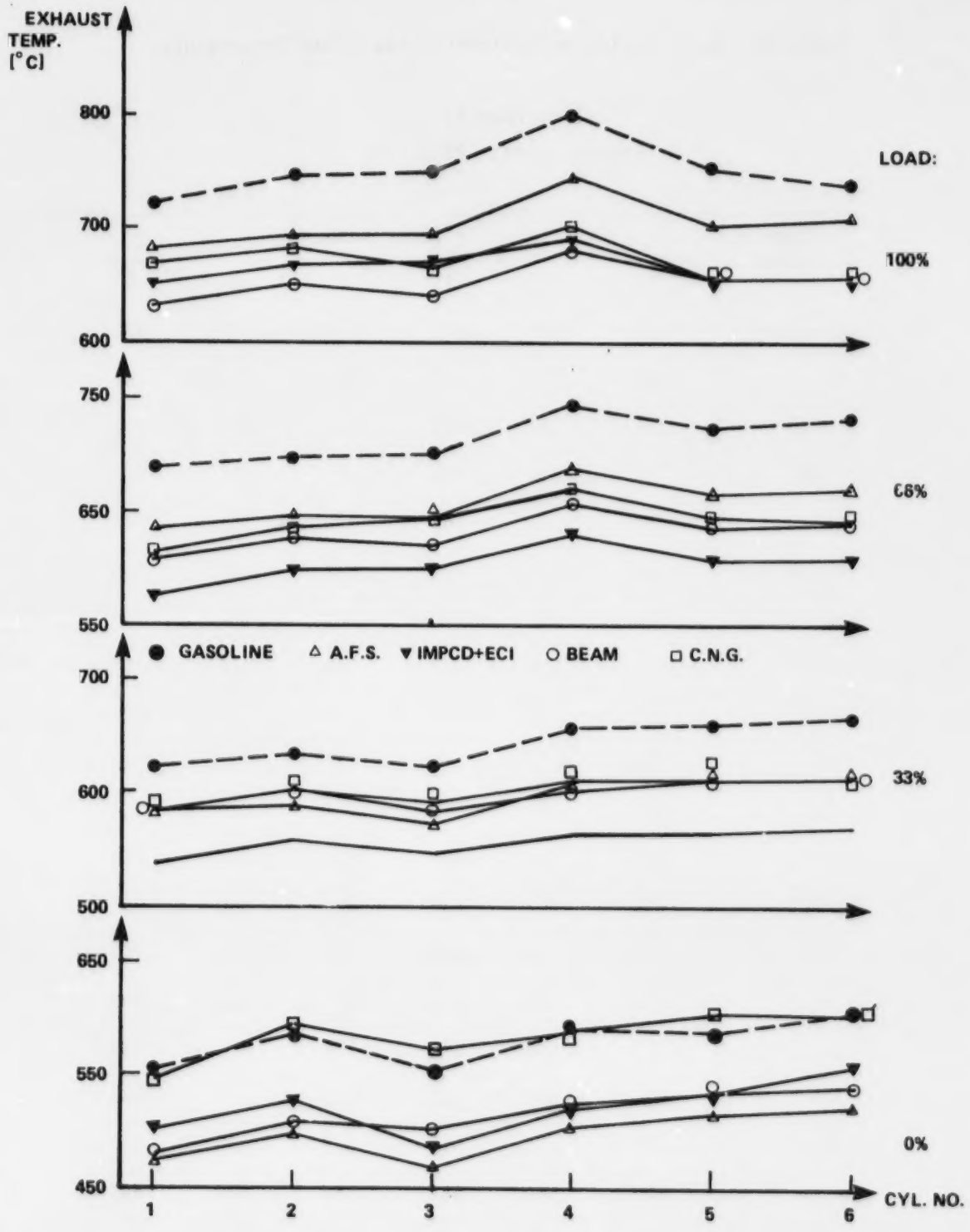

Figure 14/ Temperature Distribution in the Exhaust Ports of Cylinders at 1600 rpm

Table 22/ Distribution of Cylinder Exhaust Gas Temperatures

(°C), Average Values
Engine Speed: 2500 rpm

Load (%)	Carburation System	Cylinder Number					
		1	2	3	4	5	6
100	Gasoline	812	825	846	889	860	831
	AFS	767	778	777	824	791	781
	IMPCO	726	748	742	789	769	762
	BEAM	716	734	730	765	744	741
	CNG	759	776	767	773	741	743
66	Gasoline	768	779	793	821	802	792
	AFS	710	722	720	761	744	744
	IMPCO	675	697	702	733	714	713
	BEAM	680	710	708	739	752	721
	CNG	689	714	711	728	712	712
33	Gasoline	682	694	691	724	720	714
	AFS	669	686	681	712	707	710
	IMPCO	620	642	639	663	656	661
	BEAM	664	692	684	709	705	710
	CNG	659	685	678	693	690	692
0	Gasoline	675	698	672	706	728	737
	AFS	625	640	618	652	677	685
	IMPCO	578	625	611	629	635	646
	BEAM	627	669	654	658	670	685
	CNG	622	666	652	657	667	677

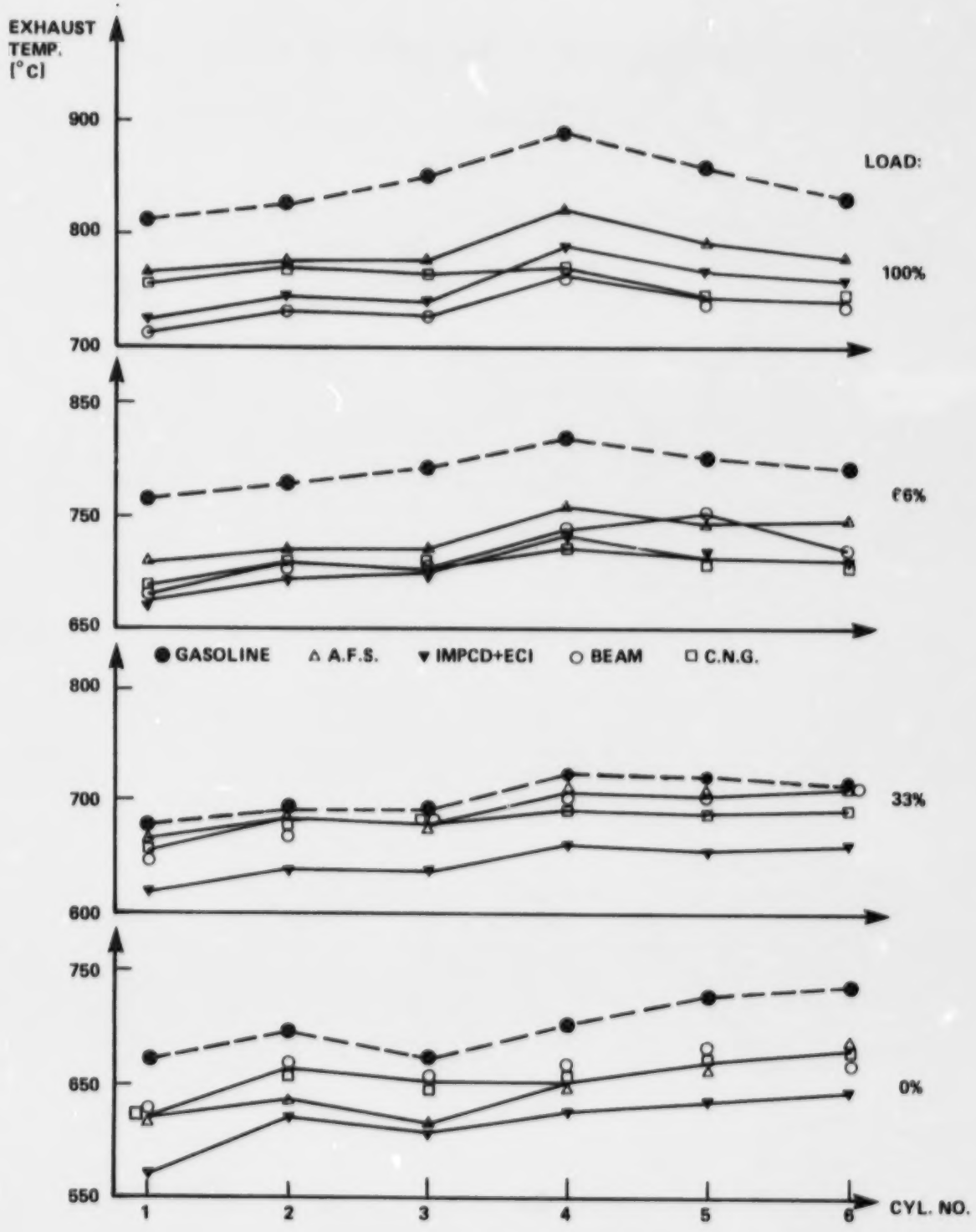

Figure 15/ Temperature Distribution in the Exhaust Port of Cylinders at 2500 rpm

Table 23/ Distribution of Cylinder Exhaust Gas Temperatures

(°C), Average Values
Engine Speed: 3500 rpm

Load (%)	Carburation System	Cylinder Number					
		1	2	3	4	5	6
100	Gasoline	863	878	891	919	904	918
	AFS	809	825	827	857	838	846
	IMPCO	791	819	809	839	841	847
	BEAM	778	836	837	856	829	797
	CNG	811	839	817	827	814	809
66	Gasoline	832	842	844	858	843	854
	AFS	777	791	785	818	811	811
	IMPCO	756	779	772	815	801	802
	BEAM	748	772	769	799	784	780
	CNG	764	796	788	799	797	781
33	Gasoline	728	745	750	767	767	766
	AFS	729	745	747	783	784	783
	IMPCO	706	729	728	751	751	747
	BEAM	720	747	740	763	760	760
	CNG	726	751	751	756	765	755
0	Gasoline	740	751	751	768	784	804
	AFS	703	718	712	725	741	757
	IMPCO	666	674	671	668	686	714
	BEAM	701	704	704	706	721	759
	CNG	695	711	714	721	734	740

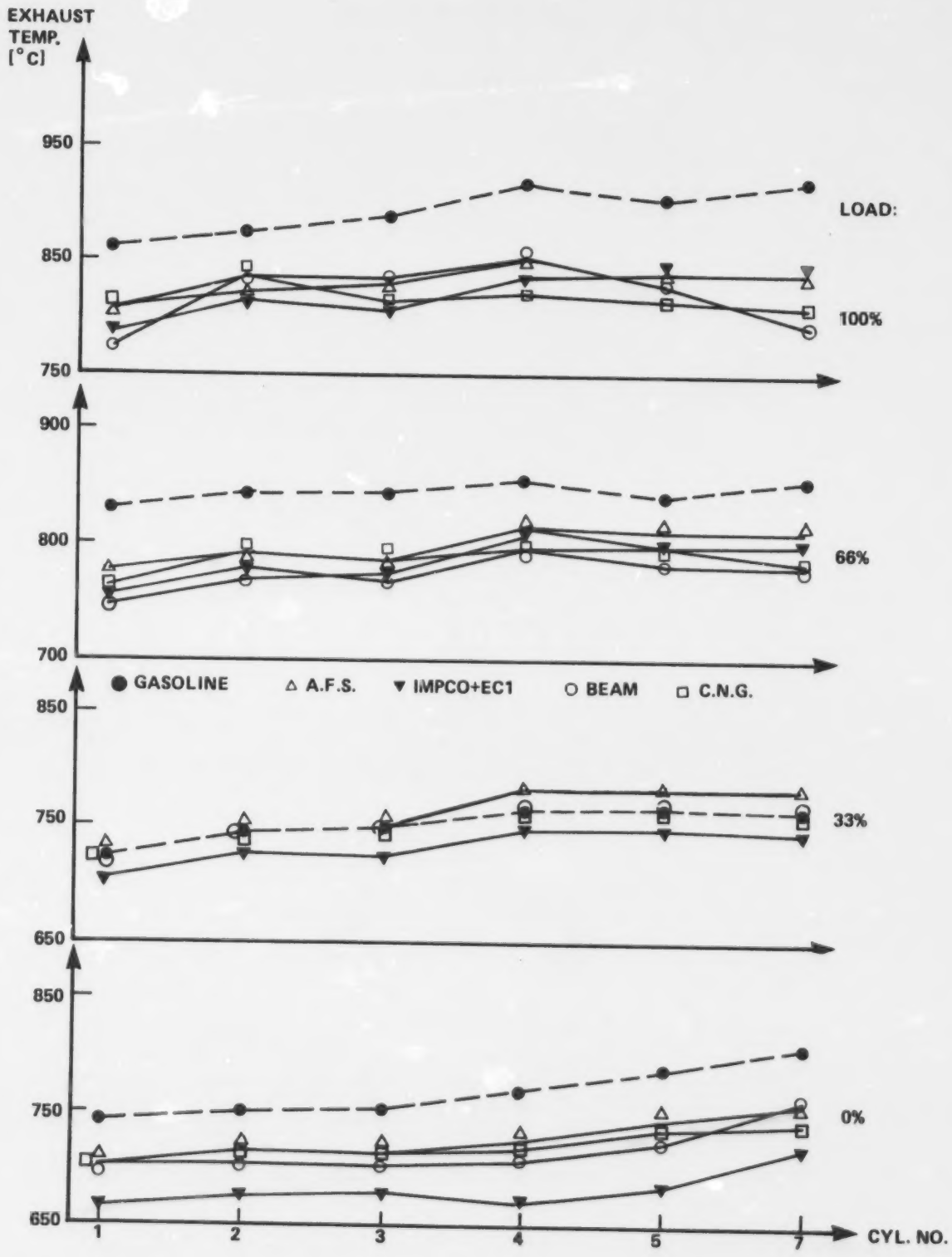

Figure 16/ Temperature Distribution in the Exhaust Ports of Cylinders at 3500 rpm

Table 24/ HC Emission

(ppm - CH_4 EQUIVALENT), Average Values

Load (%)	Carburation System	Engine Speed (rpm)				
		1600	2000	2500	3000	3500
100	Gasoline	133	116	99	120	82
	AFS	660	768	750	677	705
	IMPCO	550	760	750	805	580
	BEAM	1163	1288	1188	895	430
	CNG	645	630	400	410	280
66	Gasoline	126	95	47	40	19
	AFS	620	710	750	850	875
	IMPCO	770	700	680	890	1125
	BEAM	1013	1045	985	1018	1120
	CNG	760	730	700	625	780
33	Gasoline	127	101	75	57	42
	AFS	825	825	723	837	861
	IMPCO	1663	1175	885	760	1100
	BEAM	1263	1088	1075	1250	1438
	CNG	1088	950	790	775	890
0	Gasoline	220	192	159	66	42
	AFS	1762	888	763	605	663
	IMPCO	4500	4200	2950	1600	1438
	BEAM	3350	2000	2250	4250	7505
	CNG	800	938	1184	1013	1450

Before catalytic converter, all emission controls active, air pump isolated.

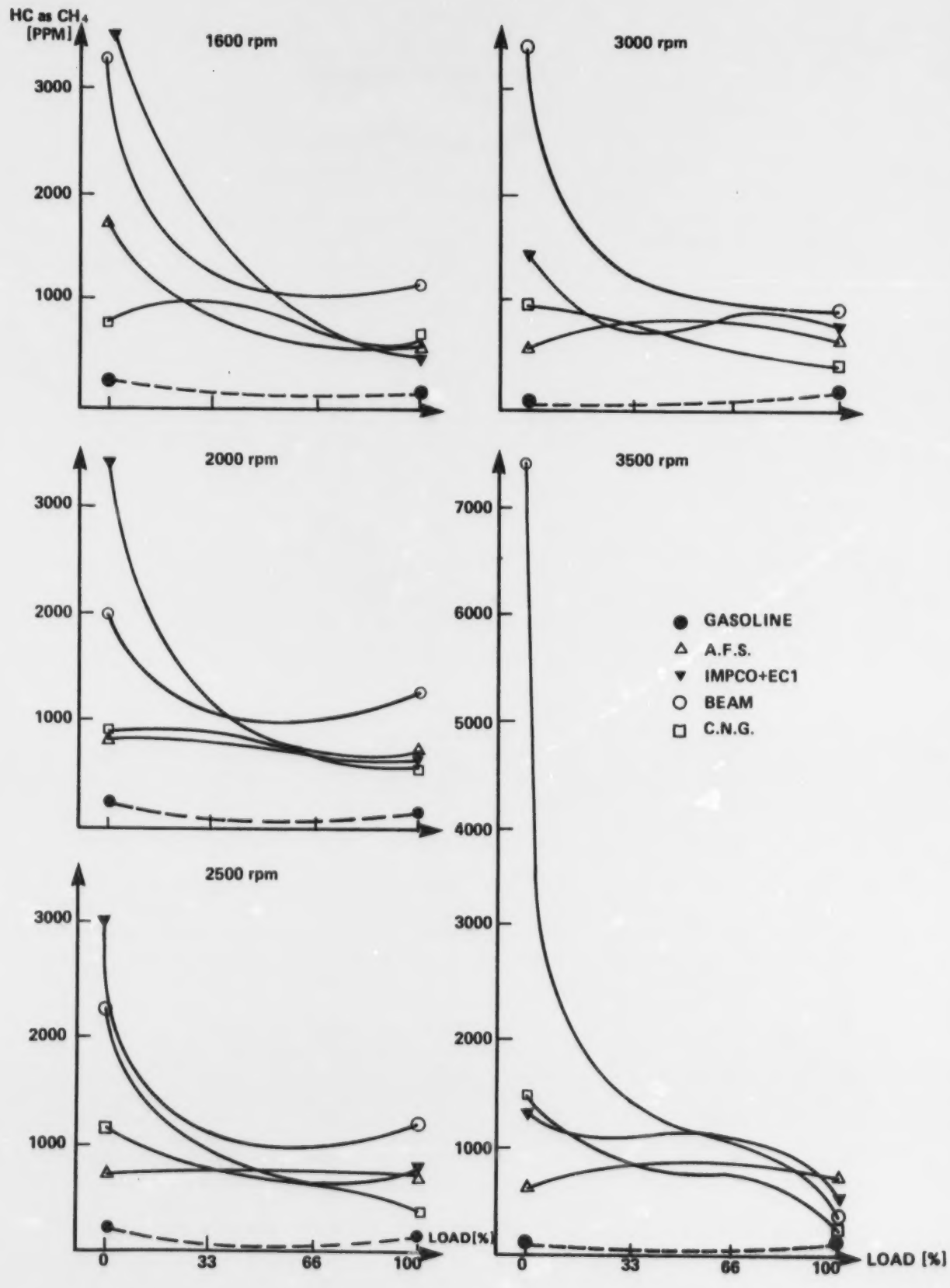

Figure 17/ HC Emission (Before Catalytic Converter; Air Pump Isolated)

Table 25/ NO Emission

(PPM), Average Values

Load (%)	Carburation System	Engine Speed (rpm)				
		1600	2000	2500	3000	3500
100	Gasoline	2413	2750	2550	2000	3150
	AFS	2213	2275	2337	1663	1662
	IMPCO	3250	3250	2525	2750	3200
	BEAM	605	588	675	2163	4250
	CNG	2750	2950	2700	2900	2550
66	Gasoline	788	1275	1288	1438	1413
	AFS	625	937	1013	925	1038
	IMPCO	720	1863	2500	2075	1775
	BEAM	925	1288	1825	1925	1900
	CNG	735	1200	1266	1475	1663
33	Gasoline	660	740	735	875	950
	AFS	560	1000	1075	1188	1325
	IMPCO	119	350	725	900	1613
	BEAM	690	1038	1150	1200	1213
	CNG	555	900	1100	1300	1513
0	Gasoline	128	260	290	350	445
	AFS	41	185	220	335	405
	IMPCO	25	37	49	88	318
	BEAM	116	188	185	270	420
	CNG	29	128	147	275	390

Before catalytic converter, all emission controls active, air pump isolated.

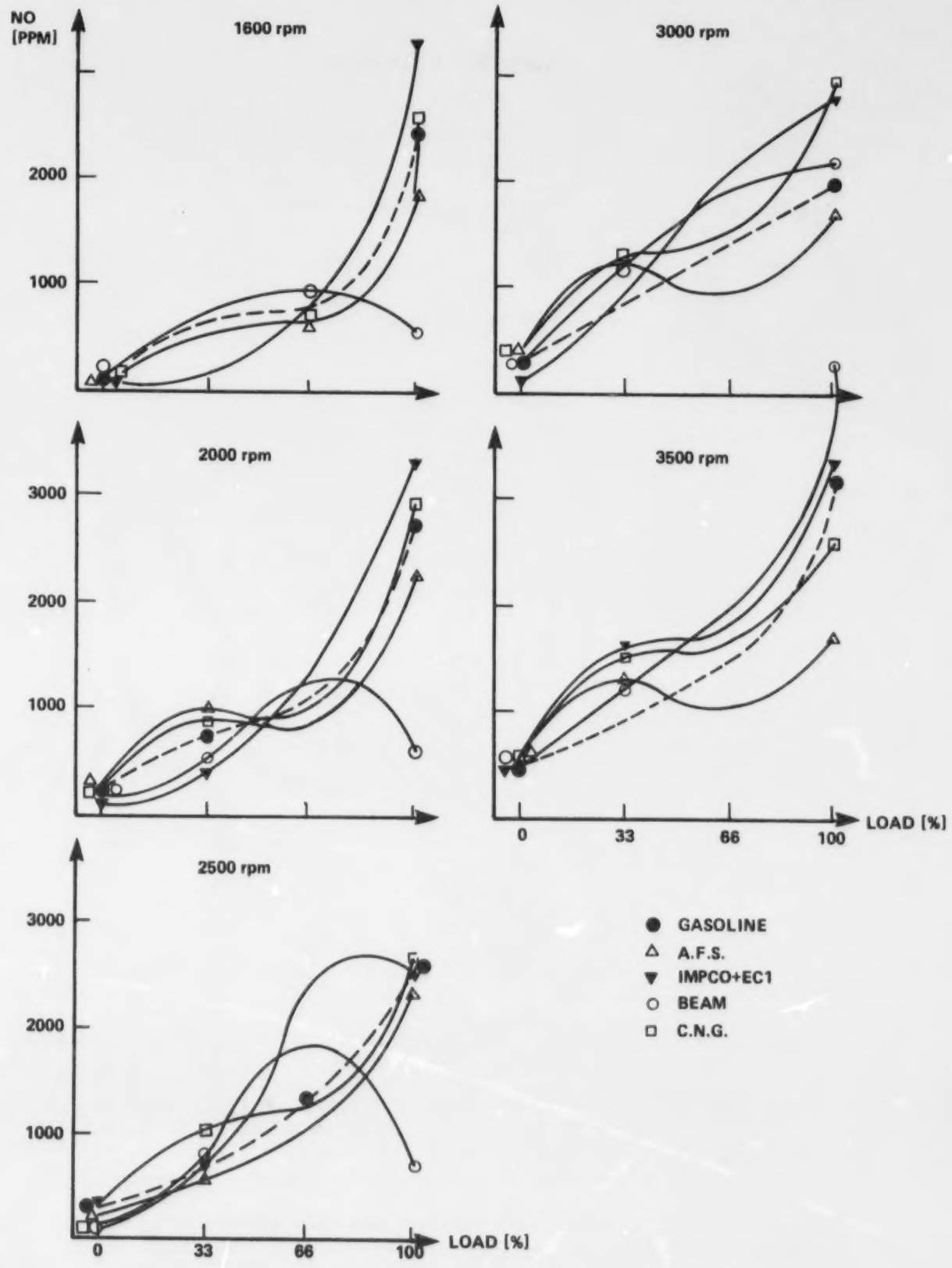

Figure 18/ NO Emission (Before Catalytic Converter, Air Pump Isolated)

Table 26/ O_2 Emission

(%), Average Values

Load (%)	Carburation System	Engine Speed (rpm)				
		1600	2000	2500	3000	3500
100	Gasoline	0.23	0.23	0.18	0.10	0.73
	AFS	0.20	0.20	0.13	0.08	0.14
	IMPCO	1.40	0.50	0.25	0.20	0.35
	BEAM	0.30	0.15	0.10	0.10	1.00
	CNG	1.15	1.20	1.30	1.05	1.05
66	Gasoline	0.50	0.78	1.45	1.80	1.68
	AFS	1.13	0.60	0.25	0.09	0.09
	IMPCO	3.70	2.50	1.30	0.50	0.20
	BEAM	0.85	0.65	0.50	0.45	0.45
	CNG	1.80	1.55	1.55	1.25	0.85
33	Gasoline	1.75	2.70	3.15	3.50	3.50
	AFS	1.85	1.37	0.80	0.30	0.23
	IMPCO	5.20	4.30	3.25	2.25	1.35
	BEAM	1.00	0.80	0.60	0.50	0.55
	CNG	1.75	1.50	1.75	1.75	1.30
0	Gasoline	0.45	0.48	0.35	1.00	1.45
	AFS	4.00	2.95	1.85	1.20	1.05
	IMPCO	7.20	6.69	5.55	4.45	3.95
	BEAM	2.75	2.35	1.75	1.60	2.10
	CNG	3.50	3.35	2.65	2.20	2.25

Before catalytic converter, all emission controls active, air pump isolated.

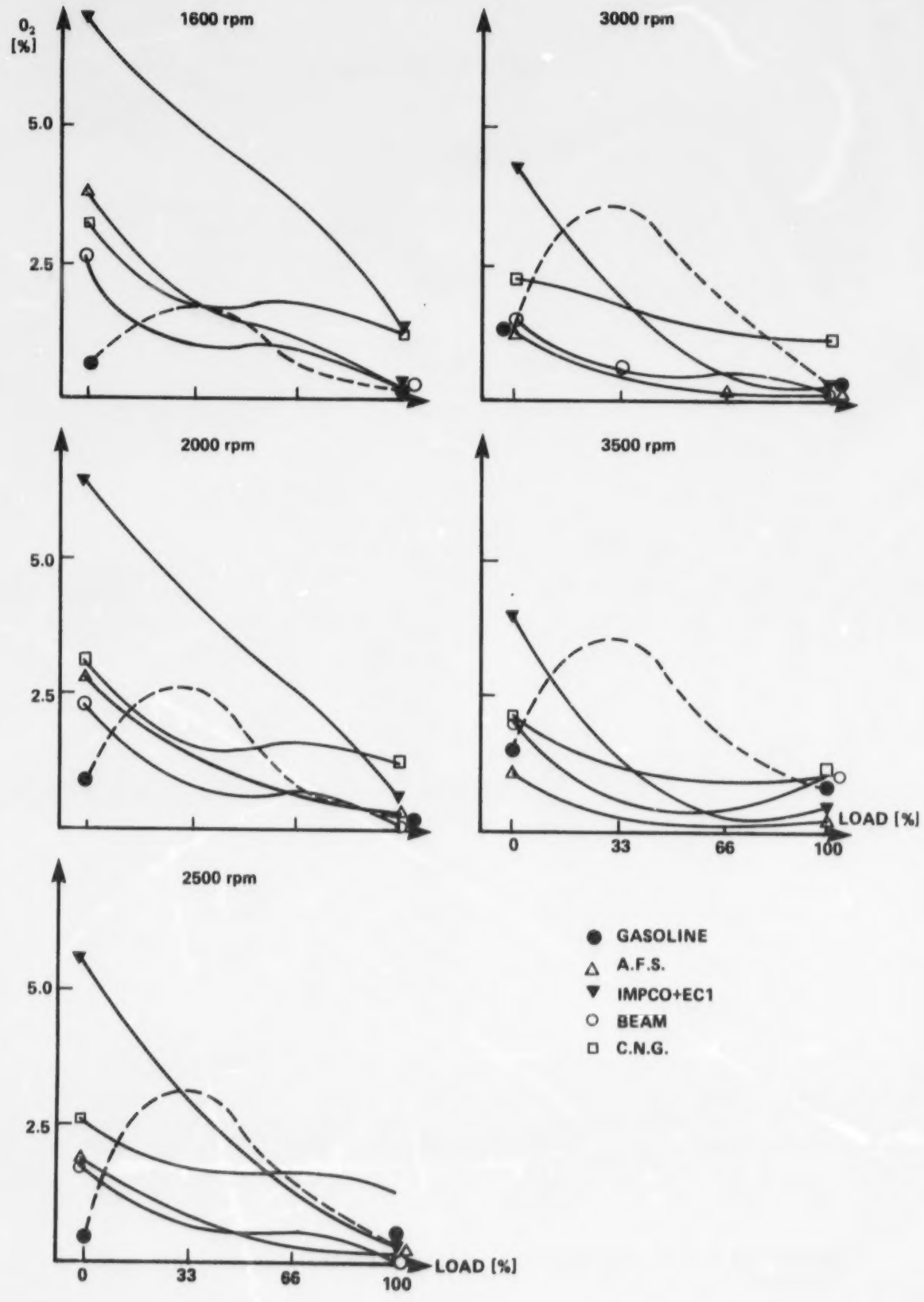

Figure 19/ O_2 Emission (Before Catalytic Converter; Air Pump Isolated)

Table 27/ CO Emission

(%) / % vs. Gasoline, Average Values

Load (%)	Carburation System	Engine Speed (rpm)				
		1600	2000	2500	3000	3500
100	Gasoline	1.23	1.02	1.25	2.65	1.33
	AFS	0.70	0.49	0.84	1.63	2.15
	IMPCO	0.02	0.31	0.98	1.47	1.29
	BEAM	0.34	0.35	0.39	1.71	0.19
	CNG	0.34	0.36	0.30	0.40	0.60
66	Gasoline	0.49	0.27	0.14	0.15	0.17
	AFS	0.04	0.06	0.12	0.80	1.00
	IMPCO	0.02	0.02	0.05	0.08	0.59
	BEAM	0.08	0.26	0.26	0.28	0.52
	CNG	0.04	0.04	0.04	0.05	0.09
33	Gasoline	0.05	0.11	0.13	0.14	0.14
	AFS	0.06	0.06	0.06	0.16	0.22
	IMPCO	0.04	0.04	0.04	0.05	0.06
	BEAM	0.07	0.08	0.18	0.28	0.50
	CNG	0.04	0.04	0.04	0.05	0.08
0	Gasoline	0.70	0.66	0.66	0.23	0.19
	AFS	0.12	0.10	0.10	0.12	0.11
	IMPCO	0.10	0.10	0.08	0.08	0.06
	BEAM	0.09	0.09	0.10	0.19	0.34
	CNG	0.07	0.08	0.07	0.09	0.09

Before catalytic converter, all emission controls active, air pump isolated.

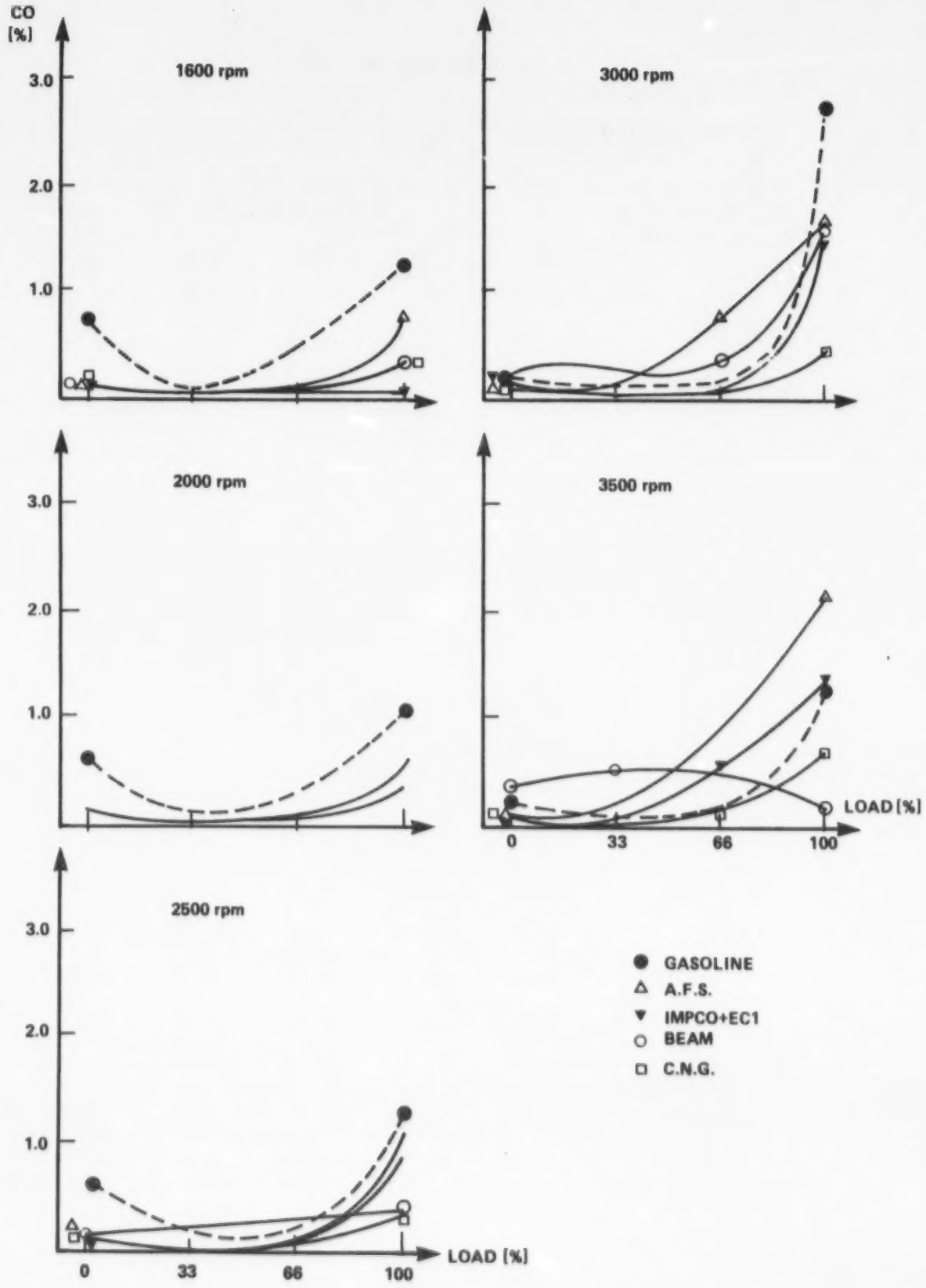

Figure 20/ CO Emission (Before Catalytic Converter; Air Pump Isolated)

Table 28/ Air-Fuel RATIO

(A/F Stoichiometric: ~14.59 for Gasoline, ~17.26 for Methane), Average Values

Load (%)	Carburation System	Engine Speed (rpm)				
		1600	2000	2500	3000	3500
100	Gasoline	14.49	14.33	14.19	13.81	15.02
	AFS	16.93	17.05	16.78	16.32	16.04
	IMPCO	18.39	17.41	16.77	16.46	16.72
	BEAM	17.04	16.87	16.82	17.06	17.99
	CNG	17.57	17.92	18.06	17.82	17.70
66	Gasoline	14.71	15.05	15.62	16.14	16.03
	AFS	17.97	17.52	17.23	16.56	16.75
	IMPCO	20.60	19.35	18.24	17.48	16.89
	BEAM	17.71	17.45	17.45	17.30	17.11
	CNG	18.53	18.34	18.26	18.13	17.47
33	Gasoline	15.91	16.76	17.19	17.48	17.51
	AFS	18.52	18.14	17.70	17.24	17.15
	IMPCO	22.26	21.17	20.02	19.01	18.15
	BEAM	17.78	17.65	17.44	17.28	17.16
	CNG	18.42	18.24	18.49	18.51	18.11
0	Gasoline	14.54	14.52	14.49	15.19	15.56
	AFS	20.32	19.61	18.51	17.97	17.85
	IMPCO	24.27	23.11	22.22	21.24	20.74
	BEAM	19.03	18.80	18.21	17.70	17.49
	CNG	20.11	19.92	19.16	18.81	18.78

Table 29/ Equivalence Air Fuel Ratio

$\frac{A/F}{A/F\ Stoich.}$, Average Values

Load (%)	Carburation System	Engine Speed (rpm)				
		1600	2000	2500	3000	3500
100	Gasoline	0.99	0.98	0.97	0.95	1.03
	AFS	0.98	0.99	0.97	0.95	0.93
	IMPCO	1.07	1.01	0.97	0.95	0.97
	BEAM	0.99	0.98	0.97	0.99	1.04
	CNG	1.02	1.04	1.05	1.03	1.03
66	Gasoline	1.01	1.03	1.07	1.11	1.10
	AFS	1.04	1.02	1.00	0.96	0.97
	IMPCO	1.19	1.12	1.06	1.01	0.98
	BEAM	1.03	1.01	1.01	1.00	0.99
	CNG	1.07	1.06	1.06	1.05	1.01
33	Gasoline	1.09	1.15	1.18	1.20	1.20
	AFS	1.07	1.05	1.03	1.00	0.99
	IMPCO	1.29	1.23	1.16	1.10	1.05
	BEAM	1.03	1.02	1.01	1.00	0.99
	CNG	1.07	1.06	1.07	1.07	1.05
0	Gasoline	1.00	1.00	0.99	1.04	1.07
	AFS	1.18	1.14	1.07	1.04	1.03
	IMPCO	1.41	1.34	1.29	1.23	1.20
	BEAM	1.10	1.09	1.06	1.03	1.01
	CNG	1.17	1.15	1.11	1.09	1.09

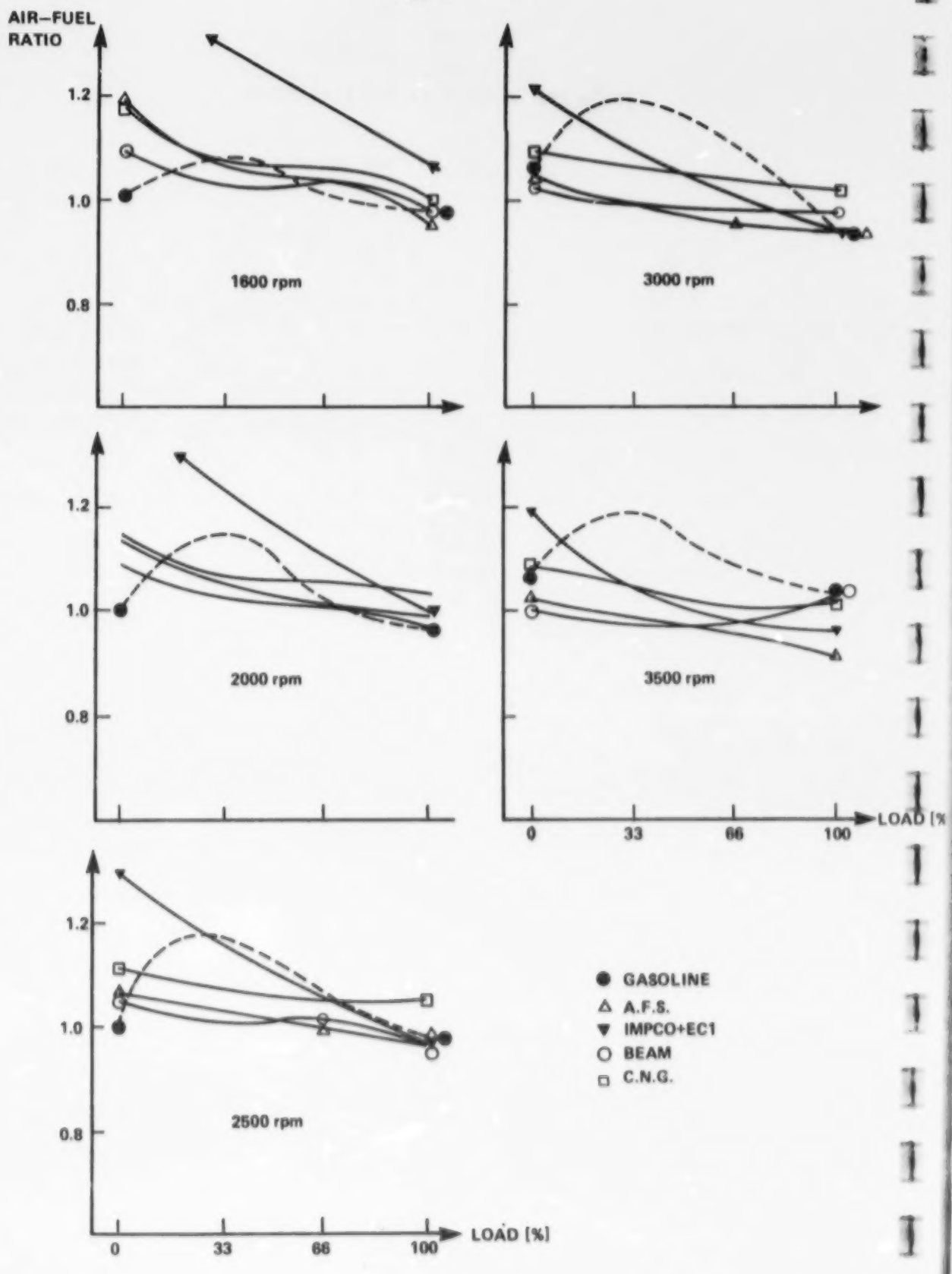

Figure 21/ Equivalence Air-Fuel Ratio

5/ SYSTEM OPTIMIZATION

5.1/ Timing and Air-Fuel Ratio

5.1.1/ Procedure

The influence of timing and air-fuel ratio is analysed according to the procedure described here, searching for maximum torque at wide open throttle and for minimum BSFC at partial loads.

5.1.1.1/ Influence of Timing at Full Load (WOT) -- see Figure 22:

- set ignition manually, isolating the vacuum advance and moving the body of the distributor until the desired timing angle is read;
- stabilize on lowest desired speed with spark retarded from the best torque timing;
- record torque and timing;
- advance spark 2° and record torque, maintaining the speed constant;
- repeat until a two-degree advance shows no improvement in torque;
- retard half interval, check that torque and speed are unchanged, run and record data at determined minimum for best torque (MBT) advance;
- repeat in speed increments to maximum test speed.

5.1.1.2/ Influence of Air-Fuel Ratio at Full Load (WOT -- See Figure 23:

- adjust carburation system, controlling the reference pressure in the third stage of regulator (AFS);
- set ignition manually as in 5.1.1.1;
- stabilize at lowest desired speed with the carburation system richer than leanest for best torque (LBT) and spark retarded from MBT setting;
- record torque, timing and air-fuel ratio;
- determine and record MBT timing at constant air-fuel ratio, as per 5.1.1.1;
- lean air-fuel mixture;
- readjust and record MBT timing and new air-fuel ratio;
- record torque;
- lean air-fuel mixture and readjust MBT timing until torque falls below

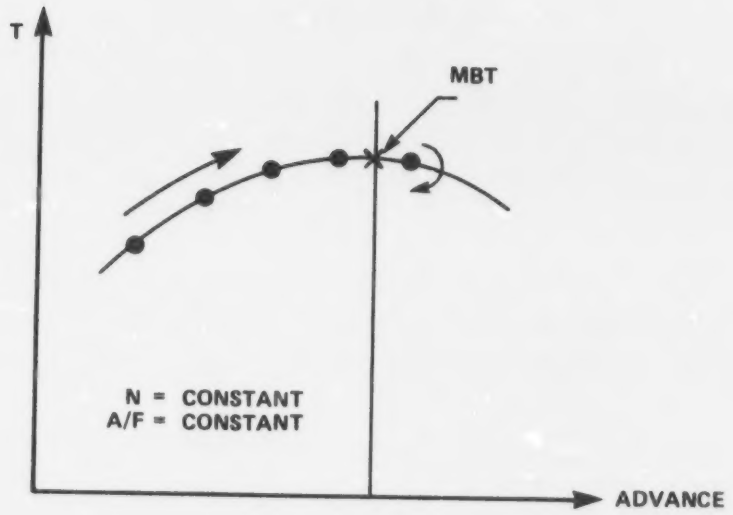

Figure 22/ Principle of Timing Optimization at Full Load, for MBT (Minimum for Best Torque)

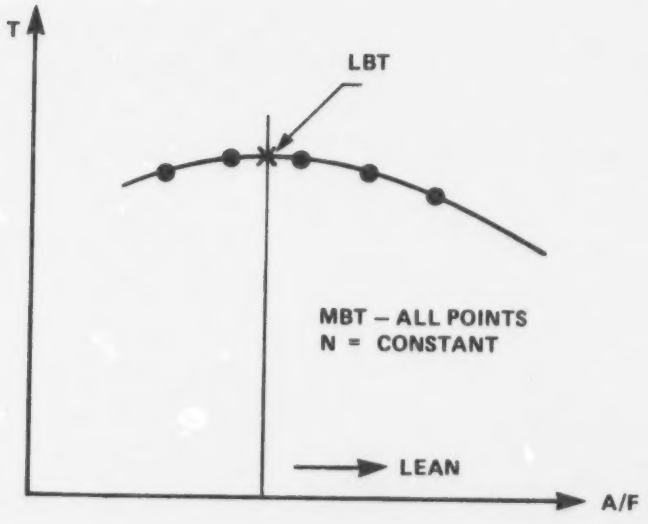

Figure 23/ Principle of Air-Fuel Ratio Optimization at Full Load, for LBT (Leanest for Best Torque)

previous value,
- adjust mixture reacher, midway between last two settings and readjust MBT timing;
- check that torque is equal to previous maximum value and speed is unchanged, run and record data at determined LBT;
- repeat in speed increments to maximum test speed.

5.1.1.3/ Influence of Timing at Partial Loads (2/3 and 1/3 of Maximum at WOT) -- See Figure 24:

- set ignition manually;
- stabilize at lowest desired speed, 2/3 or 1/3 of the MBT torque, with spark retarded from the point of minimum specific fuel consumption;
- run the test and compute BSFC;
- advance spark 3°, run the test maintaining speed and torque constant and compute BSFC;
- repeat until BSFC reaches a minimum and starts to rise again;
- retard to the point of minimum BSFC and run the test to check that the value of BSFC is unchanged;
- repeat in speed increments to maximum test speed.

5.1.1.4/ Influence of Air-Fuel Ratio at Partial Load (2/3 and 1/3 of Maximum at WOT) -- See Figure 25:

- adjust carburation system as per 5.1.1.2;
- set ignition manually;
- stabilize at lowest desired speed, 2/3 or 1/3 of the MBT torque, the carburation system richer and spark retarded from the values necessary for minimum BSFC;
- record timing and air-fuel ratio, run test and compute BSFC;
- determine timing for minimum BSFC as per 5.1.1.3;
- lean air-fuel mixture;
- determine timing for minimum BSFC at new air-fuel ratio,
- lean air-fuel mixture and readjust the timing for minimum BSFC until BSFC reaches a minimum and starts to rise again;
- retard to the midpoint between the last two tests, check that the values are unchanged;
- repeat in speed increments to maximum test speed.

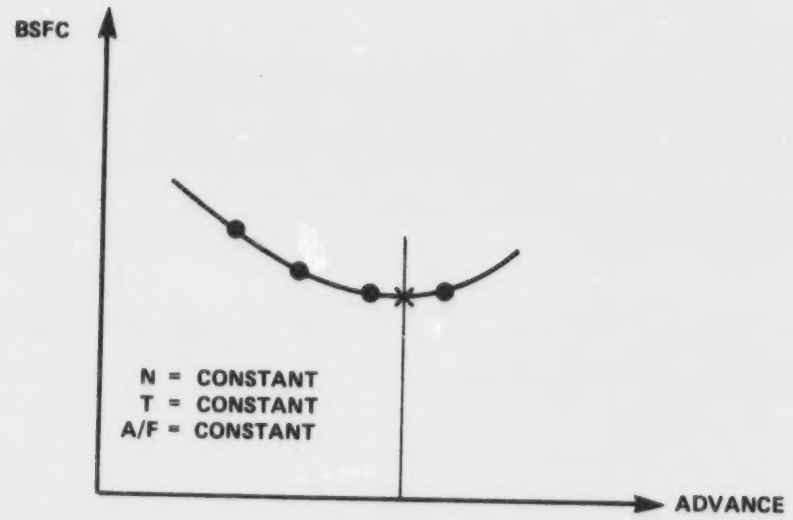

Figure 24/ Principle of Timing Optimization at Partial Loads, for Minimum BSFC (Brake Specific Fuel Consumption)

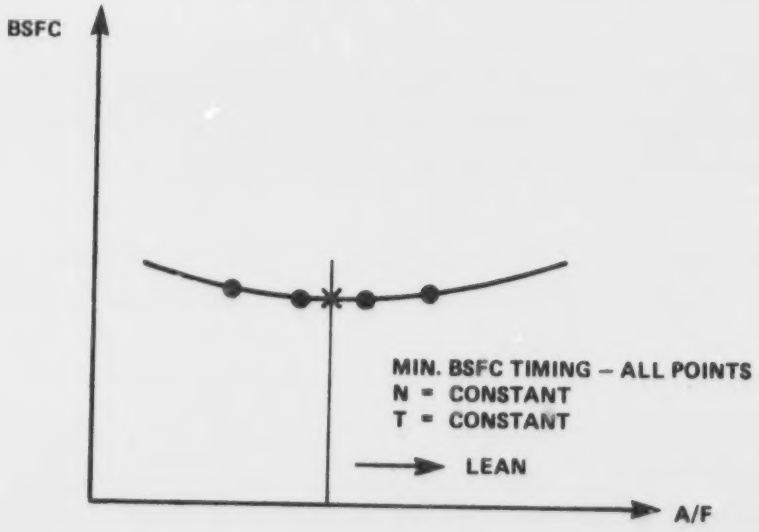

Figure 25/ Principle of Air-Fuel Ratio Optimization at Partial Loads, for Minimum BSFC

5.1.2/ Results

5.1.2.1/ Full Load Optimization

The search for MBT (minimum for best torque) timing has been done at three air-fuel ratio settings -- commercial calibration, a mixture richer and a mixture leaner by 1:1.5 points. The results are contained in Table 30 and Figure 26 to 28.

The optimum timing at commercial calibration varies between 22° at 1600 rpm and 28° at 3500 rpm, for an equivalence air-ratio of 0.95:0.97. Enriching the mixture to 0.85:0.89 results in an increased BSFC (+10.5 ÷ 14.6%) at a reduced power output (-4.2 ÷ 4.9%). Leaning the mixture to 1.03:1.05 results in up to 6.3% fuel economy, but at reduced power (-3.0 ÷ 4.9%). The trade-off between torque and specific fuel consumption can be observed in Figure 28. The maximum torque output, of great interest at WOT, can be obtained accepting a decrease in BSFC. On the other hand, minimum BSFC can be obtained accepting a decrease in the torque developed.

5.1.2.2/ Partial Loads Optimization

The results of partial loads timing and air-fuel ratio optimization are presented in Table 31 and Figures 29 to 31. The timing optimization yields the most significant improvements, as can be observed from Figure 29.

Overall, the procedure of optimization determines a reduction of specific fuel consumption between 1.9 and 7.7%, with the timing presented in Figure 31 and at equivalence air-fuel ratios of 1.00 to 1.15.

Table 30/ WOT Performance at Optimum Timing (MBT)

Change vs. Commercial Timing and A/F on AFS System

Engine A/F Calibration		Commercial			Rich		Lean		
Speed	rpm	1600	2500	3500	1600	2500	1600	2500	3500
Observed torque	N.m	276	253	196	265	241	265	246	187
Corr. power	kW	46.25	66.50	72.00	44.30	63.25	44.50	64.50	68.50
change	%	-	-	-	-4.22	-4.89	-3.78	-3.01	-4.86
OBSFC	g/kW.h	268	287	335	307	317	276	271	314
change	%	-	-	-	+14.55	+10.45	+2.99	-5.57	-6.27
Optimum timing	°	22	24	28	20	22	20	22	28
A/F	-	16.44	16.79	16.72	14.72	15.33	17.73	17.83	18.13
change A/F	-	-	-	-	-1.72	-1.46	+1.29	+1.04	+1.41
Average exhaust temperature	°C	644	734	794	633	720	658	732	730

Table 31/ BSFC Optimization at Partial Loads

Engine Speed	rpm	1600		2500		3500	
Load	%	66	33	66	33	66	33
Commercial calibration BSFC -- Mass base (AFS carburation system)	g/kW.h	260	342	279	369	379	501
Optimum BSFC -- Mass Base	g/kW.h	260	330	271	362	350	487
Change	%	0.00	-3.51	-2.87	-1.90	-7.65	-2.79
Optimum timing	°	29	43	34	43	34	46
Optimum A/F	-	~17.0	~20.0	~17.2	~17.0	~19.5	~19.0

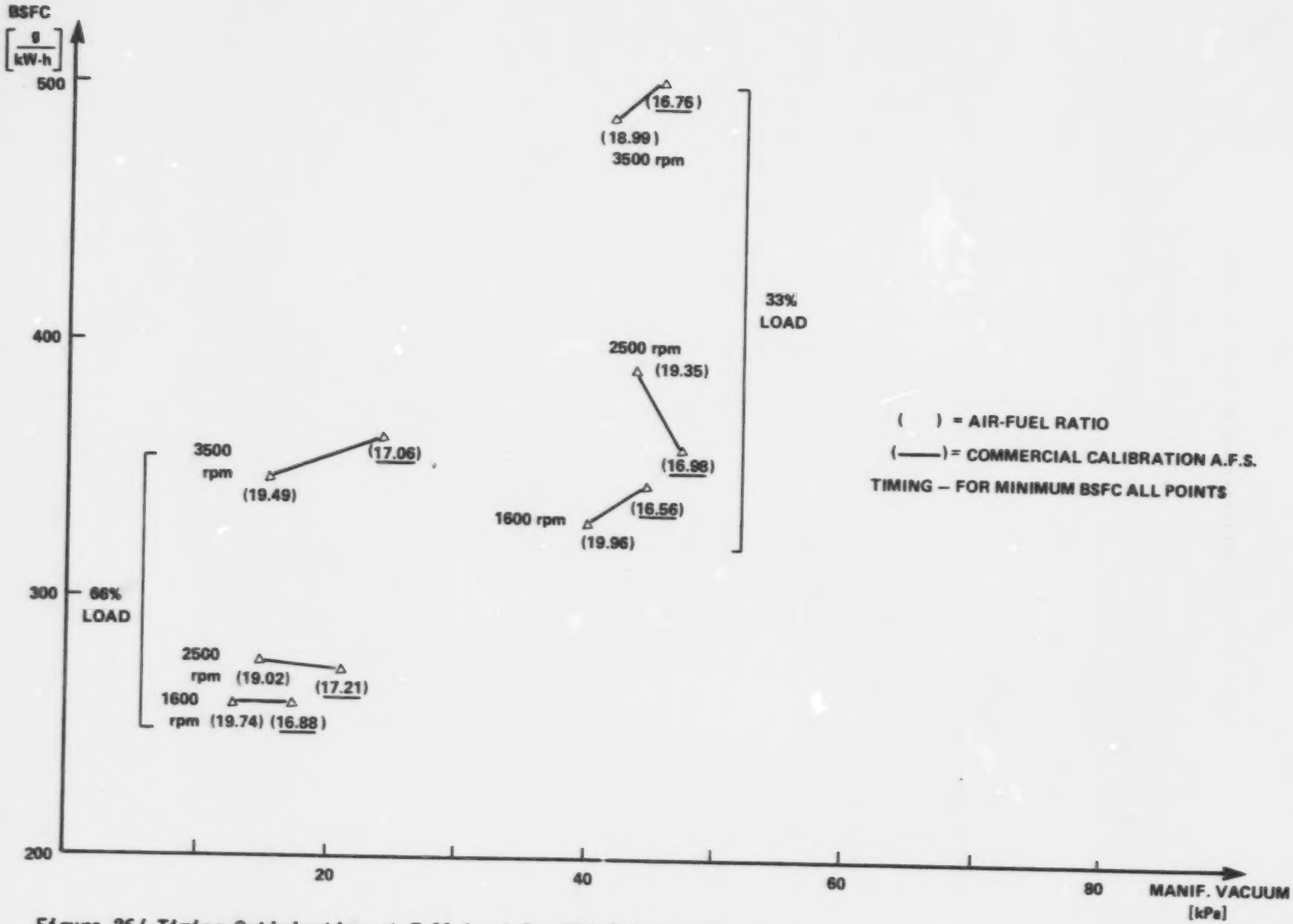

Figure 26/ Timing Optimization at Full Load for MBT (Minimum for Best Torque) -- FORD 4.9 L BF 251 Engine; Natural Gas Fuel

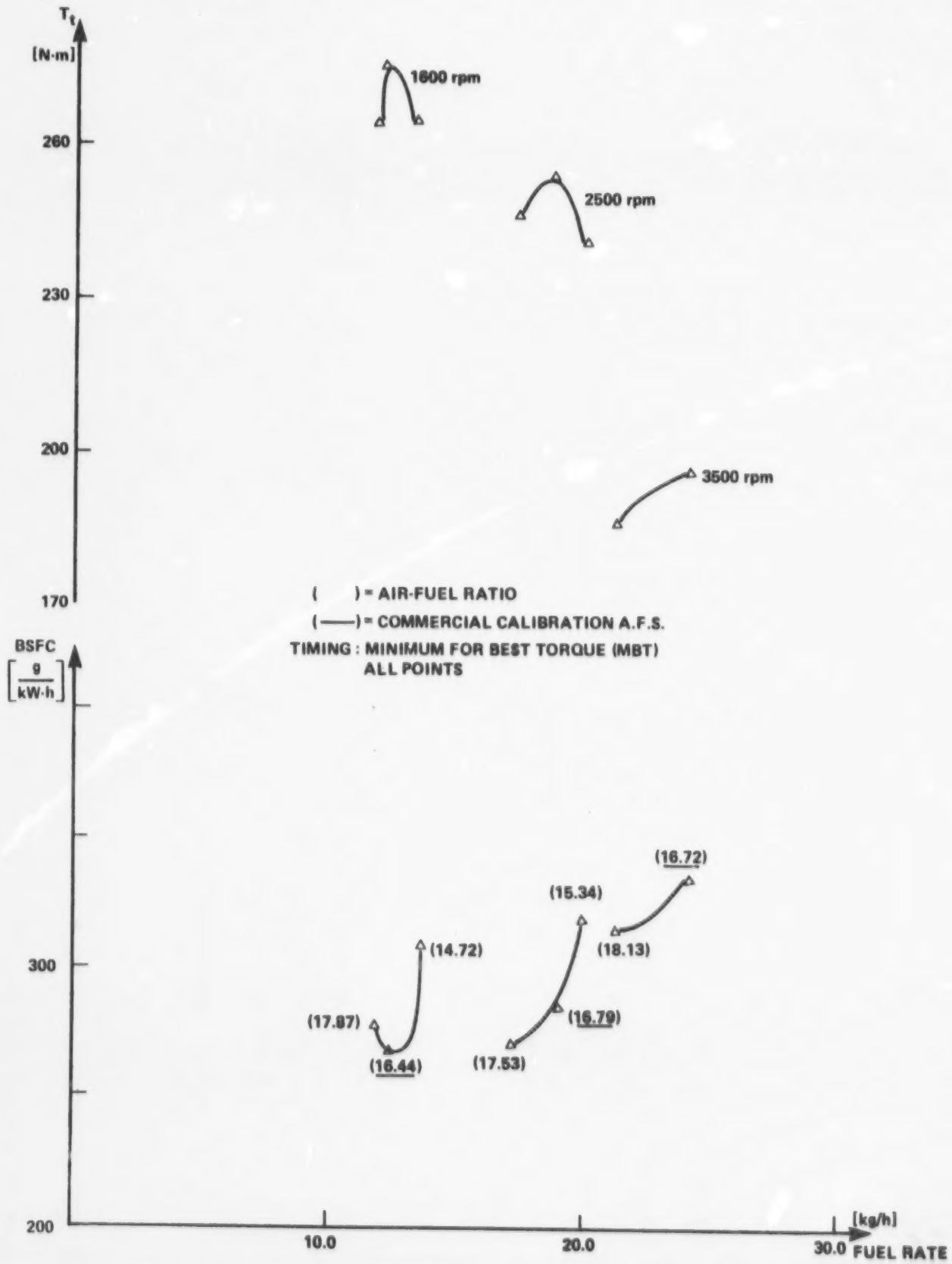

Figure 27/ Correlation Between Fuel Rate, Torque and BSFC at Full Load -- FORD 4.9 L BF 251 Engine; Natural Gas Fuel

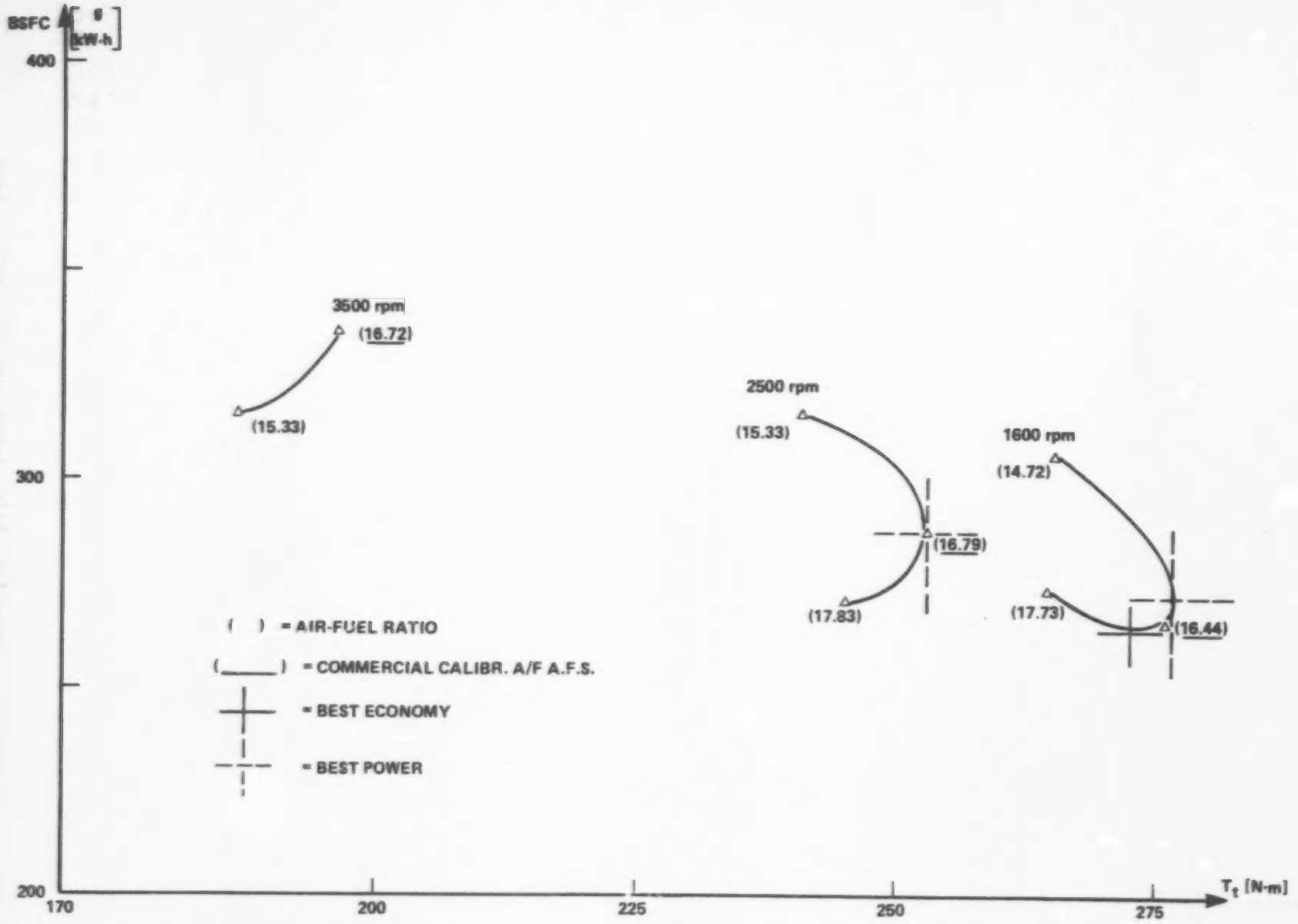

Figure 28/ Correlation Between Torque and BSFC at Full Load -- FORD 4.9 L BT 251 Engine; Natural Gas Fuel

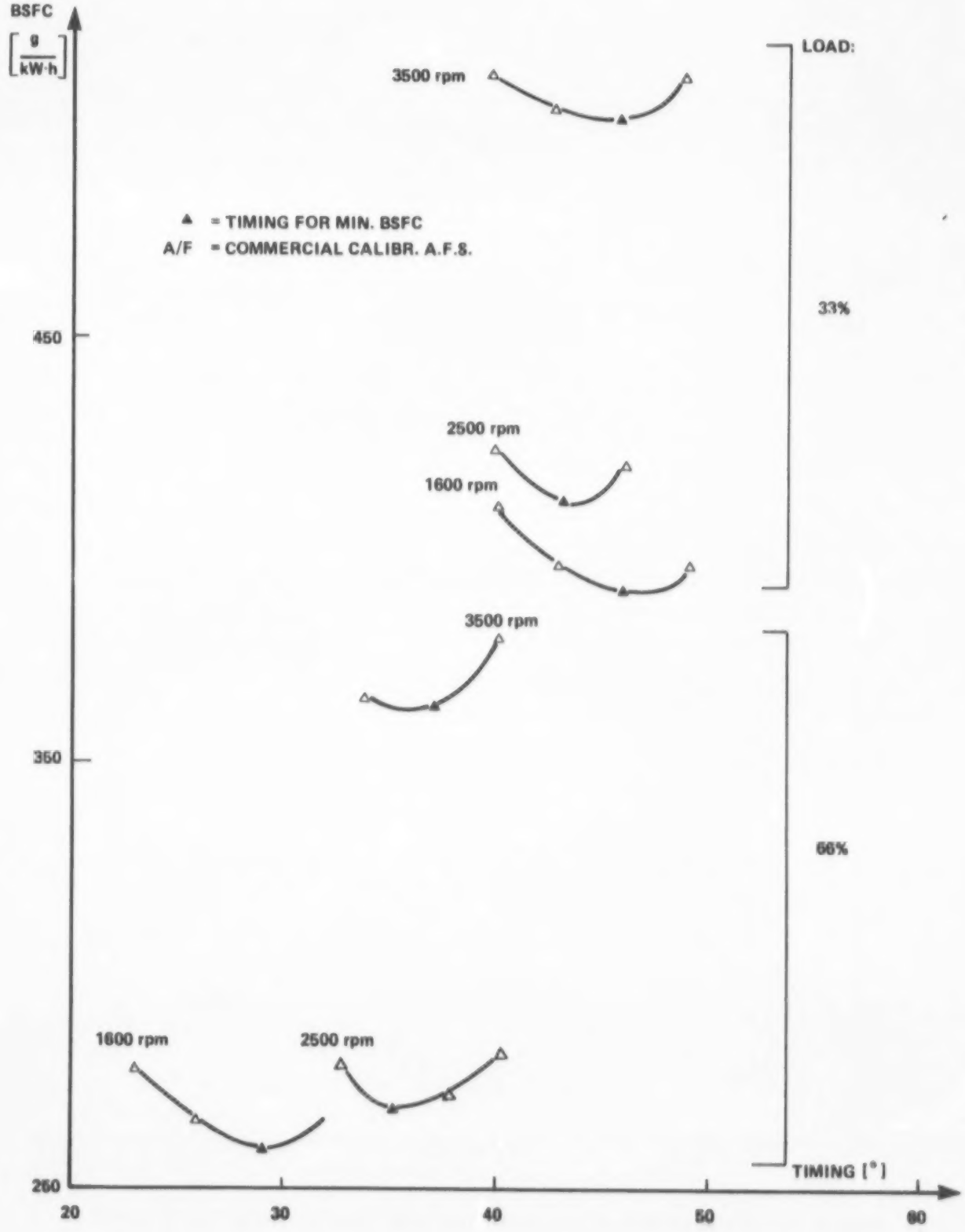

Figure 29/ Timing Optimization at Partial Loads for Minimum Timing (°)
BSFC -- FORD 4.9 L BF 251 Engine; Natural Gas

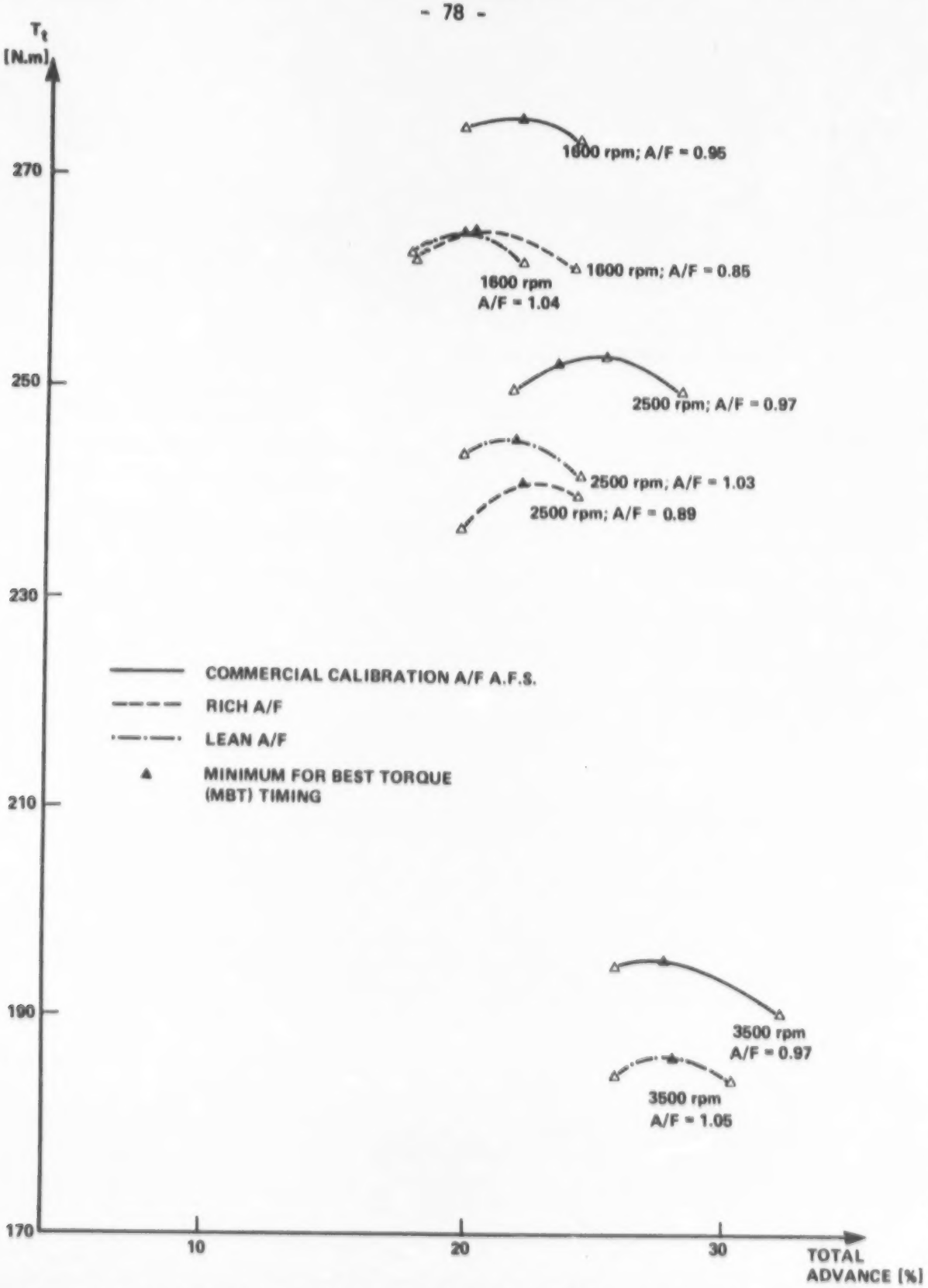

Figure 30/ Optimization of Air-Fuel Ratio at Partial Loads for Minimum BSFC -- FORD 4.9 L BF 251 Engine; Natural Gas Fuel

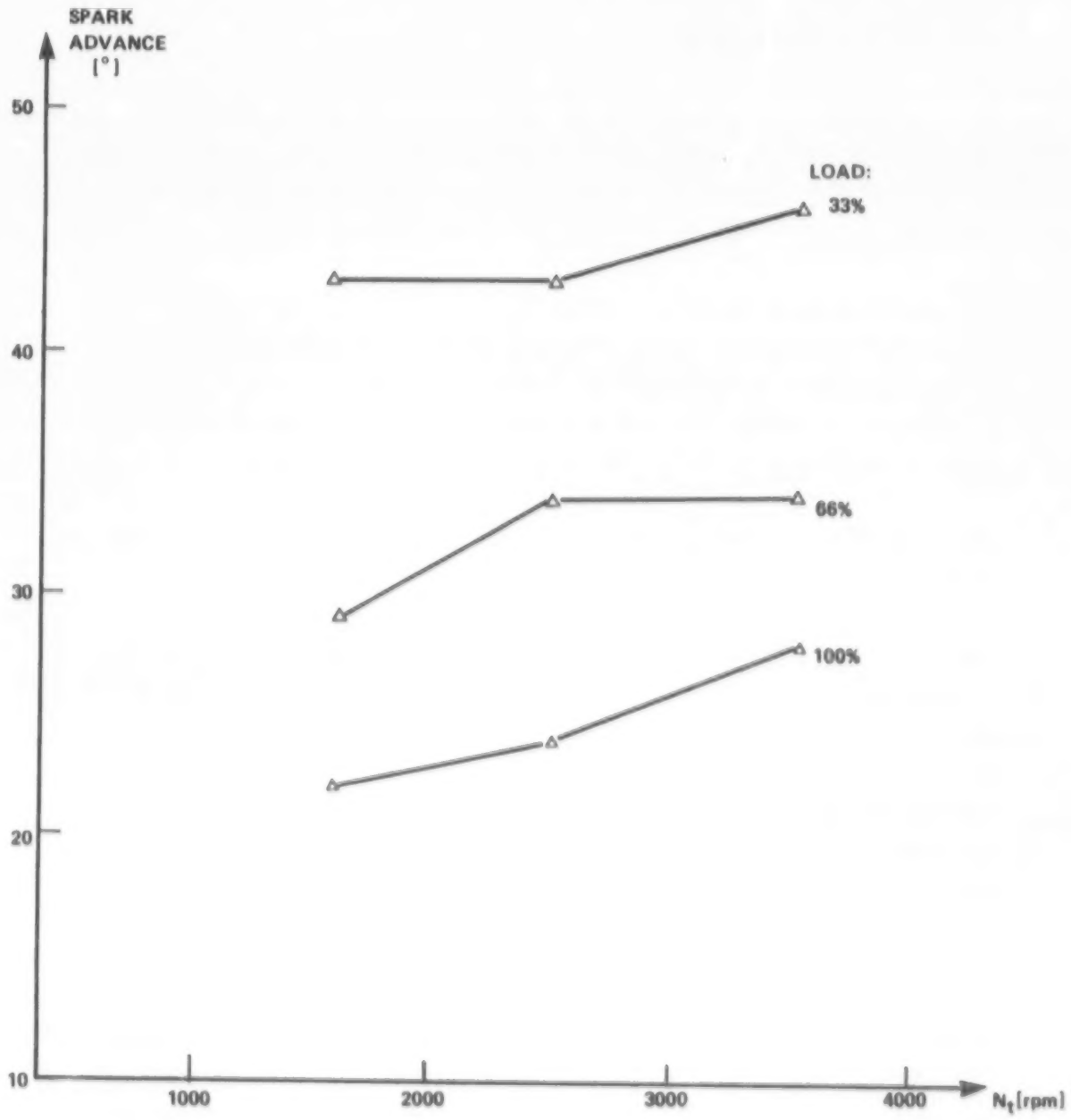

Figure 31/ Optimum Total Timing -- FORD 4.9 L BF 251 Engine; Natural Gas Fuel

5.2/ Ignition Enhancement

As a continuation of the effort to improve the economy of natural gas use as an engine fuel, a number of hardware changes were made in the ignition system with the purpose of increasing the voltage, spark energy, and spark plugs heat value and gap for this slow burning fuel.

The equipment used is listed below:

- "Mallory" electronic coil #29150 oil-impregnated high-voltage output coil for electronic breakerless ignition systems,
- "Mallory" "Hy-Fire" electronic ignition control, designed to increase the spark energy by 50 to 70% (e.g., from 150 to 250 mJ at idle).

The tests have been conducted at 2500 rpm and WOT, 2/3 and 1/3 of the load.

The use of the high-voltage coil plus spark plugs two steps hotter did not change the results. Increasing the gap of the spark plugs by 50% in the some configuration resulted in reduced performance. Adding the Hy-Fire control restored the initial performance, without improvement. Increasing further the spark plug gap another 50% did not change the performance, reducing only the specific fuel consumption by 2 ÷ 3% at partial loads.

5.3/ Cooling Water Temperature

To establish the influence of a lower temperature of the cooling water -- as practiced very often for propane -- a test was run with the thermostatic control set at 71°C (160°F). The only noticeable result was an increase in specific fuel consumption, ranging from 14% at low speeds, to 9% at high speeds.

5.4/ EGR Valve Action

Continuing the comparison with the practice of propane use, where the emission controls are disconnected, a test was run with the EGR valve isolated. This resulted in a two to three times increase in NO emission, accompanied by a 10 to 15% increase in specific fuel consumption.

6/ CONCLUSIONS

- The maximum power developed using natural gas is 12.3 to 22.1% lower than for gasoline.

- The energy efficiency of the engine is reduced by 13.8 to 25.8% for natural gas, as an average for the four carburation system tested. For individual testing points, the limits range from 12.6% increased efficiency to 51.2% reduction.

- The best carburation systems tested show narrower limits of energy efficiency change, between 6.4% improvement and 9.8% reduction.

- Through the timing and air-fuel ratio optimization performed by our laboratory, a further increase of energy efficiency at partial loads between 1.90 and 7.65% was achieved.

- Other modifications of the ignition system at the same level of "conversion" -- without major engine changes, like increased ignition energy, spark gap and voltage, show little or no effect on performance and economy.

- Unlike the conversion to propane, with combustion properties closer to gasoline, the conversion to natural gas done in the same manner results in reduced power output and fuel efficiency. With a density 2.5 times lower than propane, the natural gas requires specially designed mixers, of larger sizes, to insure the proper mixing of the fuel and air in the right proportions. The "universal" pressure regulators and mixers used now for propane and natural gas alike are far from satisfying these requirements. After admission of the mixture into cylinders, the low combustion speed of natural gas determines an incomplete combustion during the time available in the engine cycle.

- The exhaust temperature for natural gas are consistently lower than for gasoline, due to the combustion properties of the fuel.

- The very high level of hydrocarbons emission and the level of carbon monoxide increasing with speed far quicker than for gasoline, prove the unsatisfactory combustion in cylinders.

- The necessary improvements in the use of the natural gas as an automotive fuel cannot be initiated before gaining a deeper understanding of the basic combustion characteristics of this fuel.

7/ FUTURE WORK

The big potential of the natural gas as an automotive fuel, determined by its availability, cost and high octane rating, can be exploited if a program of research is initiated to optimize its use.

The basic combustion properties of the natural gas when used as an engine fuel have to be investigated in a one cylinder variable compression research engine, determining the influence of different parameters on performance, economy and emissions. The information available is not enough to permit development work to be done.

Methods of efficient fuel metering as function of load and speed and thorough mixing with air have to be developed. The results of such a development program can be beneficial for other gaseous fuels (hydrogen, propane), too.

Based on the conclusions of these two phases, a multicylinder engine can be modified with higher compression ratio and improved valve timing, fuel metering, mixing and cylinders charge density increase.

APPENDIX A/ Calculations for Corrected Parameters

$$bp_t = \frac{N_t \cdot T_t}{9549} \quad (1)$$

bp_t (kW) = brake power, observed at test conditions
T_t (N.m) = torque, observed
N_t (rpm) = speed, observed

$$F_t = W_t \cdot \frac{60}{M} \quad (2)$$

F_t (g/h) = fuel consumption per hour
W_t (g) = mass of fuel consumed during the test
M (min) = test duration

$$bsfc = \frac{F_t}{bp_t} \quad (3)$$

bsfc (g/kW.h) = brake specific fuel consumption

$$bmep_t = 6 \cdot 10^7 \cdot \frac{bp_t \cdot 2}{D \cdot N_t} \quad (4)$$

$bmep_t$ (kPa) = brake mean effective pressure, observed
D (cm^3) = engine displacement
2 = engine revolutions per cycle, for 4 cycles engine

$$n = \frac{100}{1 + \frac{6.8947 \cdot x - y \cdot bmep_t}{bmep_t}} \quad (5)$$

n (%) = mechanical efficiency

where:

$$x = 16.3761 + 2.28629 \frac{N_t}{1000} + 0.297053 \left(\frac{N_t}{1000}\right)^2 \quad (6)$$

$$y = \frac{1}{100}\left[5.44659 - 0.02495\,\frac{N}{1000} + 0.174376\left(\frac{N}{1000}\right)^2\right] \quad (7)$$

$$fp_t = bp_t\left(\frac{100}{n} - 1\right) \quad (8)$$

fp_t (kW) = friction power

$$B_{dt} = B_t - e_t \quad (9)$$

B_{dt} (kPa) = barometric pressure-dry air
B_t (kPa) = measured barometric pressure
e_t (kPa) = water vapour pressure (table)

$$C_s = \frac{97.93}{B_{dt}} \cdot \sqrt{\frac{t_t + 273}{302.4}} \quad (10)$$

C_s = correction factor for atmospheric conditions
97.93 (kPa) = standard barometric pressure
302.4 = 29.4 + 273 (°C) = standard temperature

$$bp_c = (bp_t + fp_t) \cdot C_s - fp_t \quad (11)$$

bp_c (kW) = corrected brake power

$$Tc = \frac{9545}{N_t} \cdot bp_c \quad (12)$$

T_c (N.m) = corrected torque

$$bmepc = 1.2 \cdot 10^8 \cdot \frac{bp_c}{D \cdot N_t} \quad (13)$$

$bmep_c$ (kPa) = corrected brake mean effective pressure

APPENDIX B/ Calculation of Air-Fuel Ratio from Exhaust Gas Constituents (1,2,3)

The combustion reaction for a hydrocarbon fuel with air may be expressed as:

$$CH_y + (n)O_2 + (3.76\ n)N_2 > (a)CO_2 + (1 - a - 6c)\ CO + (b)H_2O$$

$$+ (c)C_6H_{14} + (d)NO + \left(\frac{Y}{2} - b - 7c\right)H_2$$

$$+ \left(n - a - \frac{1 - a - 6c}{2} - \frac{b}{2} - \frac{d}{2}\right)O_2 + \left(3.76\ n - \frac{d}{2}\right)N_2 \qquad (1)$$

for one atom of carbon, in which:

( ) = mol of constituents for 1 mol of fuel CH_y (bracketed coefficient)

y = fuel atomic H/C ratio

C_6H_{14} = unburned hydrocarbon, reported as hexane

For a nondispersive infrared (NDIR) analyser, the term (HC) can be multiplied by a factor of 1.8, to account for the lack of response to certain exhaust HC species (for flame ionization detectors -- FID -- the factor is 1.0).

Defining a "fuel conversion factor" N:

$$N = \frac{\text{mol exhaust}}{\text{mol fuel}} = \frac{100}{6(HC) + (CO) + (CO_2)} \qquad (2)$$

( ) = molar percent (bracketed species) expressed in (%), and summing the mols of products from Equation 1:

$$N = a + (1 - a - 6c) + w + c + d\left(\frac{Y}{2}\ b - 7c\right)$$

$$+ \left(n - a - \frac{1 - a - 6c}{2} - \frac{b}{2} - \frac{d}{2}\right) + \left(3.76\ n - \frac{d}{2}\right) \qquad (3)$$

in which mols of water produced b are replaced by w, mols of water at analyser, following any condensation. With no condensation, w = b.

$$N = 4.76\ n - 6c + \frac{1 - a - 6c - 3b + y}{2} + w \qquad (4)$$

For the reactants in Equation 1:

$$\frac{\text{mol air}}{\text{mol fuel}} = n + 3.76\ n = 4.76\ n \qquad (5)$$

combining Equation 4 and 5:

$$\frac{\text{mol air}}{\text{mol air}} = N + 6c - \frac{1 - a - 6c}{2} + \frac{3b}{2} - \frac{Y}{2} - w \qquad (6)$$

and because:

$$\frac{\text{mol X}}{\text{mol fuel}} = \frac{\text{mol X}}{\text{mol exhaust}} \cdot \frac{\text{mol exhaust}}{\text{mol fuel}} = \frac{(X)}{100} \cdot N \qquad (7)$$

Equation 6 becomes:

$$\frac{\text{mol air}}{\text{mol fuel}} = N + \frac{6(HC)}{100} \cdot N - \frac{(CO)}{200} \cdot N + \frac{3(H_2O)}{200} \cdot N - \frac{y}{2} - \frac{(H_2O)a}{100} \cdot N \qquad (8)$$

where $(H_2O)_a$ is water concentration (%) at analysers

$$\frac{A}{F} = \frac{\text{g air}}{\text{g fuel}} = \frac{\text{mol air}}{\text{mol fuel}} \cdot \frac{\text{M air}}{\text{M fuel}} \qquad (9)$$

where M refers to molecular weight

$$\frac{A}{F} = \frac{\text{M air}}{\text{M fuel}} \left\{ N + \frac{N}{100} \left[6(HC) - \frac{(CO)}{2} + \frac{3(H_2O)}{2} - (H_2O)_a \right] - \frac{Y}{2} \right\} \qquad (10)$$

Assuming a fixed value for the water-gas equilibrium

$$k = \frac{(CO)(H_2O)}{(CO_2)(H_2)} = 3.8 \qquad (11)$$

and with

$$(H_2) = \left(\frac{y}{2} - b - 7c\right)\frac{100}{N} = \frac{y}{2} \cdot \frac{100}{N} - (H_2O) - 7\,(HC) \qquad (12)$$

$$(H_2O) = \frac{\frac{y}{2} \cdot \frac{100}{N} - 7(HC)}{\frac{(CO)}{k\,(CO_2)} + 1} \qquad (13)$$

From Equation 10 and 13, a carbon balance air-fuel ratio can be expressed as:

$$\frac{A}{F} = \frac{M\ air}{M\ fuel}\left[\frac{100 + 6(HC) - \frac{(CO)}{2} + \frac{3\,(H_2O)}{2} - (H_2O)}{6(HC) + (CO) + (CO_2)}\,a - \frac{y}{2}\right] \qquad (14)$$

in which:

$$(H_2O) = \frac{y\,[(CO_2) + (CO)]}{2\left[\frac{(CO)}{3.8(C_2)} + 1\right]} \qquad (15)$$

Molecular weights.

$M\ air = 28.96$

$M\ fuel = M_C + y\ M_H = 12.01 + 1.008\ y$

An oxygen balance independent of the amount of water and diluents is also derived:

$$n = a + \frac{1 - a - 6c}{2} + \frac{b}{2}\ \ \frac{d}{2} + \left(n - a - \frac{1 - a - 6c}{2} - \frac{b}{2} - \frac{d}{2}\right) \qquad (16)$$

$$n = \frac{N}{100}\left[(CO_2) + \frac{(CO)}{2} + \frac{(H_2O)}{2} + \frac{(NO)}{2} + (O_2)\right] \qquad (17)$$

$$\frac{A}{F} = 4.76\ n\,\frac{M\ air}{M\ fuel} \qquad (18)$$

$$\frac{A}{F} = 4.76 \frac{M\ air}{M\ fuel} \frac{N}{100} \left[(CO_2) + \frac{(CO)}{2} + \frac{(H_2O)}{2} + \frac{(NO)}{2} + (O_2) \right] \quad (19)$$

or

$$\frac{A}{F} = 4.76 \frac{M\ air}{M\ fuel} \left[\frac{(CO_2) + \frac{(CO)}{2} + \frac{(H_2O)}{2} + \frac{(NO)}{2} + (O_2)}{6(HC) + (CO) + (CO_2)} \right] \quad (20)$$

In Equations 14 or 20, the molar concentration (HC) is multiplied by 1.8 if the analyser is non-dispersive infrared.

The oxygen balance computation of air-fuel ratio for 31 samples of exhaust analysis quoted in Table A-1 of Reference [1], resulted in an average error of +0.2352 comparative to measured values of air and fuel mass flows.

If the unburned hydrocarbons are reported as methane (CH_4), using a FID analyser, the equation 20 can be written:

$$\frac{A}{F} = 4.76 \frac{M\ air}{M\ fuel} \left[\frac{(CO_2) + \frac{(CO)}{2} + \frac{(H_2O)}{2} + \frac{(NO)}{2} + (O_2)}{(HC) + (CO) + (CO_2)} \right] \quad (21)$$

The air-fuel ratio values in this report are calculated using Equation 21 and 15 and using --

for gasoline:

$$y = \frac{H}{C} = \frac{13}{7} = 1.857$$

considering the commercial gasoline $\simeq C_7H_{13}$

$$M_f = M_C + y\, M_H = 12.01 + 1.008 \cdot 1.857 = 13.882$$

$$\left(\frac{A}{F}\right)_{stoich.} = 14.59$$

for natural gas (methane)

$$y = \frac{H}{C} = \frac{4}{1} = 4.00$$

$$M_f = M_C = y\, M_H = 12.01 + 1.008 \cdot 4 = 16.042$$

$$\left(\frac{A}{F}\right)_{stoich.} = 17.26$$

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[2] Stivender, D.L., Kim, Y.G., "Dynamic Computer Techniques for Vehicle Emission Development," SAE Paper 720211.

[3] GM Test Code, VI Edition, 1975, pp. 170; "Air-Fuel Ratio Determination from Exhaust Gas Constituents".